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New Tools for Coast Guard Research of the Rough Water Performance of Personal Flotation Devices (PFDs)

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16. Abstract

This report presents a progress overview of the joint U.S. Coast Guard and Transport Canada sponsored project to develop new research tools for evaluating personal flotation devices. The calm water method of testing has been a safe method for determining the gross in-water characteristics of an attached PFD. However, calm water testing practices cannot address the effects of wave action on PFDs. The U.S. Coast Guard and Transport Canada entered into a Joint Research Project Agreement (JRPA) in 1992 to develop new research tools to improve our understanding of the complicated effects of rough water on the performance of PFDs. A computer simulation program was developed by adapting the Articulated Total Body (ATB) human body dynamics program to a water forces environment. This program is called the Water Forces Analysis Capability (WAFAC). A sophisticated Sea Water Instrumented Manikin (SWIM) has been constructed and will be evaluated as a standard for testing PFDs and will be used to validate the computer simulation program.

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METRIC CONVERSION FACTORS

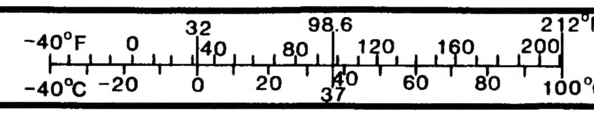
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

INTRODUCTION

This report presents a progress overview of the joint U.S. Coast Guard and Transport Canada sponsored project to develop new research tools for evaluating personal flotation devices (PFDs). Both the U.S. and Canadian approval process requires a human subject to enter calm water wearing a candidate PFD. The subject simulates unconsciousness and the PFD is evaluated for flotation and righting ability. The calm water method of testing has been a safe method for determining the gross in-water characteristics of an attached PFD. Testing small children and adults even in calm water conditions involves some level of risk. However, calm water testing practices cannot address the effects of wave action on PFDs.

OBJECTIVE

The U.S. Coast Guard and Transport Canada entered into a Joint Research Project Agreement (JRPA) in 1992 to develop new R&D tools to improve our understanding of the effects of rough water on the performance of PFDs. A number of research efforts have been performed in the past couple of years which will contribute to a future computer simulation capability. A computer simulation capability would provide a safe and cost-effective approach to testing new survival system products on various cross sections of the boating population.

NEW TOOLS DEVELOPED

The computer simulation software is based on an adaptation of the Articulated Total Body (ATB) Model. The ATB program is used to evaluate the three dimensional dynamic response of a system of rigid bodies when subjected to a dynamic environment. This human body dynamics program has been used for many years to study victim response to aircraft ejections and automobile crashes. The program was adapted by applying a water forces environment to the model refered to as the Water Forces Analysis Capability (WAFAC).

A sophisticated Sea Water Instrumented Manikin (SWIM) has been constructed and will be evaluated as a standard for testing PFDs and used to validate the computer simulation program. SWIM has the anthropomorphic characteristics of a 50th percentile midsize male with the appropriate dimensional, inertial, center of gravity, and joint properties. The manikin developed was leveraged off of several proven manikins including the HYBRID II, HYBRID III, and Advanced Dynamic Anthropomorphic Manikin (ADAM). SWIM has a 32-channel self-contained instrumentation system which records 21-segment joint positions, linear and angular accelerations of the chest, and body attitude pressure sensors.

FUTURE WORK

Validation of the model is required before any practical application of the computer software can take place. The testing scheduled to begin late in 1997, at the Institute for Marine Dynamics in St. Johns Newfoundland, will be exploratory in nature. The objectives of the first phase of testing will be to validate the SWIM manikin and to explore the limitations of the WAFAC model with SWIM whole body experiments. The second phase of testing would consist of developing a test device to attach to the undercarriage of the towing tank. The device will provide forced oscillations to derive hydrodynamic coefficients for each joint over a range of test speeds.

ACKNOWLEDGMENTS

The U.S. Coast Guard and Transport Canada gratefully acknowledge the cooperation of the many organizations and companies in performing the efforts discussed in this report. Table 1 in this report provides an overview of research participants and respective points of contact.

TABLE of ACRONYMS

ADAM	Advanced Dynamic Anthropomorphic Manikin
ATB	Articulated Total Body Program
DAS	Data Acquisition System
DOF	Degree of Freedom
DTRC	David Taylor Research Center
DYNAMAN	*PC Adaptation of ATB Program*
GEBOD	Generator of Body Data
HELP	Heat Escape Lessening Posture
HYBRID II (III)	*Manikin Standards used in the Automotive Industry*
IMD	Institute for Marine Dynamics in St. Johns, Newfoundland
JRPA	Joint Research Project Agreement
LSI	Life Saving Index
PFD	Personal Flotation Device
SWIM	Sea Water Instrumented Manikin
SWIMVU	*Program Developed to Animate SWIM's Experimental Motions*
TOR	Technical Operating Requirements
WAFAC	Water Forces Analysis Capability
WPAFB	Wright Patterson Air Force Base

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1.0 INTRODUCTION

1.1 Research Goals

The primary goal of this research is to develop a validated computer simulation capability to predict the dynamic behavior of persons wearing PFDs in rough water conditions. A computer simulation would provide a safe and cost-effective approach to testing new survival system products on various cross sections of the boating population. The end product is envisioned as being a public domain design tool that survival equipment manufacturers can use to optimize their concepts and new products.

The secondary goal is to utilize both the program and instrumented manikin to design experiments to study the factors which are most important to survival in a man-over-board scenario. This will improve the Coast Guard's understanding of the effects of waves on the person wearing a PFD and will lead to the development of the best possible standards for PFD testing and approval, i.e., improved LSI data or new rough water indices.

1.2 WAFAC Overview

The first research tool needed was a suitable human body dynamics program for adaptation to a water forces environment. The Articulated Total Body model (ATB) was identified as a proven design tool used by the U.S. Air Force and automotive industry for studying victim response to aircraft ejection's and crashes. The ATB model was created by adding an aerodynamic force and harness belt capability to the Crash Victim Simulation (CVS) Program used by National Highway Transportation Safety Administration (NHTSA). The ATB Model is used to evaluate the three dimensional dynamic response of a system of rigid bodies when subjected to a dynamic environment. The environment consists of applied forces and interactive contact forces. The ATB model is used to model both dynamic human and manikin behavior. The program considers the body as being segmented into individual rigid bodies. Each segment has the characteristic mass of the body between body joints and mass moments-of-inertia. The maximum number of segments that can be modeled is presently limited to thirty but typically 17 segments are considered adequate. Segments are added where deemed necessary for added emphasis in certain parts of the body. This program was adapted by applying a water forces environment to the model referred to as the Water Forces Analysis Capability (WAFAC).

1.3 SWIM Overview

The second tool required was a suitable instrumented flotation manikin to serve as both a computer model validation and survival testing tool. A manikin was desired that could accurately represent the anthropometric characteristics of a real person. This was essential because of the potential contribution of the position of a person's arms and legs to his or her actual flotation response and flotation attitude. The manikin developed was leveraged off of several existing and proven manikins such as the HYBRID II, HYBRID III, and

Advanced Dynamic Anthropomorphic Manikin (ADAM) to help defray developmental costs. The newly developed manikin is referred to as the Sea Water Instrumented Manikin (SWIM).

SWIM has a 32 channel self-contained instrumentation system which records 21-segment joint positions, linear and angular accelerations of the chest, and body attitude pressure sensors. SWIM has body segments with adjustable buoyancy, a bladder that surrounds the chest to duplicate the change in air volume retained in the lung between an unconscious and conscious person taking a full breath, and removable lead ballast to simulate persons whose body mass makes them inherently sink or float. SWIM has a splash collection to quantify the amount of water ingested by wave splashes and an emergency flotation device to ensure that SWIM will resurface if it submerges.

2.0 BACKGROUND

2.1 The U.S. Coast Guard's Lifejacket Responsibilities

The U.S. Coast Guard and Transport Canada have the legal approval authority on new lifejacket designs in North America. The Coast Guard strives to establish the best possible lifejacket performance requirements for the recreational boating community. Recreational boating fatalities, as reported in the annual U.S. Department. of Transportation Boating Statistics, have decreased over the past couple of decades. This is a result of improved boater education and more comfortably designed Personal Flotation Devices (PFDs). However, there continues to be a steady number of fatalities in which drowned persons are recovered with their PFDs attached. Some of these deaths may be attributed to inadequate PFD design for rough water conditions. PFD designs will continue to evolve as will the need for better performance standards. For example, the recent boom in personal water craft usage will increase consumer demand for more wearable PFDs.

Testing practices are well established for evaluating the performance of PFDs in calm water, but up until now there have not been adequate tools to bridge the gap in understanding how calm water performance predictions equate in a rough water environment. Testing of PFDs have been performed using human subjects including children. Evaluating PFD performance on humans in anything but the calmest of conditions has drawbacks because it is extremely difficult for subjects to remain passive. Test repeatability has been difficult, and testing persons in rough water increases risk considerably.

2.2 Lifejacket Testing Practices

PFDs generally encompass several types of flotation aids from Type I to Type V's. Type I has the greatest buoyancy and is the most effective in rough water. The Type II's turning action is slower than the Type I but is more comfortable to the wearer. Type III is not designed to turn the wearer face up but is usually the most comfortable. The Type IV

includes throwable devices that are grasped and held by the user or thrown to a person who has fallen overboard. A Type V PFD is approved for restricted uses such as board sailing but may not be suitable for other recreational boating activities. The term PFD will for the purposes of this report refer to those PFDs that can be donned as a lifejacket.

The U.S. Coast Guard approval process requires a human subject to enter calm water wearing the candidate PFD. The subject simulates unconsciousness and the PFD is evaluated for flotation and righting ability. The U.S. Coast Guard has both structural and performance standards and procedures for approval of PFDs. As an example, an excerpt from the U.S. Code of Federal Regulations (Title 46) stipulates the following approval test requirements for the approval of PFDs:

§160.176-13 Approval Tests

"(4) Some tests in this section require a lifejacket to be tested while being worn. In each of these tests the test subjects must represent a range of small, medium, and large heights and weights. Unless otherwise specified, a minimum of 18 test subjects, including both males and females, must be used. The test subjects must not be practiced in the use of the lifejacket being tested. However, they must be familiar with the use of other Coast Guard approved lifejackets. Unless specified otherwise, test subjects must wear only swim suits. Each test subject must be able to swim and relax in the water.

NOTE: Some tests have inherent hazards for which adequate safeguards must be taken to protect personnel and property in conducting the tests."

"(4) Average requirements. The test results for all subjects must be averaged for the following static measurements and must comply with the following:
  (i) The average freeboard prior to positioning the head for maximum freeboard must be at least 120 mm (4.75 in.);
  (ii) The average torso angle must be between 30° and 50° (back of vertical); and
  (iii) The average face-plane angle must be between 20° and 50° (back of vertical).

(5) "HELP" Position. Starting in a relaxed, face-up position of static balance, each subject brings the legs and arms in towards the body so as to attain the "HELP" position (a fetal position, but holding the head back). The lifejacket must not turn the subject face down in the water.

2.3 U.S. Coast Guard Research

The U.S. Coast Guard has been sponsoring PFD research since the early 1970s. This research has generally been limited to static calm water flotation evaluations. The underlying reason for the universal acceptance of calm water approval testing of new products and calm water research studies is that it is a safe and somewhat repeatable method for determining the gross in-water characteristics of a PFD. The lack of an available rough water standard has limited approval and research to calm water.

2.3.1 1970's to 1980's

Until as recently as the 1980's, PFDs have only been tested in calm water. Rough water testing was conducted in 1983 (in Reference (1)) at the David Taylor Research Center (DTRC) with human subjects in a wave making tank. These tests provided qualitative information on the effects of different PFDs on persons in rough water. Recommendations were made to evaluate the repeatability of testing PFD designs in rough water by using instrumentation to measure such items as head angle and the number of mouth and nose immersions. There are questions that calm water methods cannot address such as:

- effects of wave action on the turning moment of PFDs
- the position that should be taken by the person wearing a PFD relative to a wave front, i.e., the optimum angle of repose for his body and head angle ,
- the number of mouth immersions that can be expected
- how much buoyancy is adequate in rough water

In 1988, DTRC collected quantitative data on factors influencing the performance of PFDs (Reference(2)). Experiments were performed on a simplistic flotation dummy referred to as "Sierra Sam" and human subjects to evaluate the natural periods of oscillation in calm water. DTRC indicated the need for new research tools and recommended the acquisition of a set of anthropometric manikins for standardization of testing and the application of the Air Force's human body dynamics simulation program.

Although a survivor's primary concern in rough water will be his or her maintenance of airway freeboard, a secondary yet important additional concern is hypothermia. The physical activity required to maintain freeboard, distance from the mouth to the water's surface, in rough water will increase heat loss. In 1985, a study was conducted by the Coast Guard to evaluate the cooling rates of human volunteers wearing Coast Guard operational protective garments in cold sea-water under calm versus rough sea conditions (Reference (3)). The results of this experiment showed significantly faster body cooling rates in rough seas than in calm seas for the subjects wearing a thermal float coat, aviation anti-exposure coveralls, and boat crew coveralls. Significantly higher heart rates were measured in the rough water for all garments tested. The loose fitting protective garments,

i.e., coveralls, performed the worse because of the wave-induced cold water flushing through the garment.

2.3.2 Life Saving Index

The U.S. Coast Guard has the responsibility to ensure that all PFDs it approves have a high probability of saving the life of boaters. Therefore, the U.S. Coast Guard is exploring the use of the Life Saving Index (LSI) as an alternative compliance path for PFDs. The LSI is a risk-based approach that could allow for improved comfort or effectiveness in a PFD design to compensate for a slight reduction in operational reliability, e.g., inflatables versus inherently buoyant PFDs. Essentially, the LSI is summarized as a number between zero and one that represents the overall lifesaving potential of a PFD design. It is based on a probability model with components of in-water effectiveness (E), reliability (R), and wearability (W),

$$LSI = E \times R \times W$$

Experiments with an instrumented flotation manikin and computer model sensitivity studies could provide invaluable insight and more meaningful indices for the in-water effectiveness of new designs, especially in areas of quantifying freeboard and self-righting performance in both calm and rough waters.

2.4 U.S. and Canadian Joint Research Project Agreement

An international joint project was arranged between Transport Canada and the U.S. Coast Guard because both agencies had embarked along a similar research path in 1992 and because research dollars were and continue to be scarce for this type of long-term research (Reference (4)).

The methods of cooperation outlined in Section 5 of the agreement are as follows.

5.1a Both parties will exchange reports embodying significant research results from their activities subject to restrictions on distribution of proprietary or other sensitive data.

5.1b Researchers from both countries will participate in workshops and conferences organized by the Department of Transportation or Transport Canada to address specific PFD research issues or to provide a mechanism for the formal or informal exchange of information.

5.1c Both parties will exchange operational and assessment data and participate in the definitional phase of experimental facility planning.

5.1d Both parties will cooperate in studies to evaluate the benefits and cost of potential applications for PFD research.

5.1e Researchers from both countries will be invited to inspect experimental test facilities and to witness and/or participate in tests related to PFD research.

5.1f Both parties will exchange any developed software packages for studying the performance of personal flotation devices.

The participating program representatives are the Ship Safety Branch for Transport Canada and Lifesaving & Fire Safety Standards (G-MSE) for the U.S. Coast Guard. The joint project goals are to jointly award a contract for the development of an instrumented anthropometric flotation manikin and to develop a validated computer simulation capability for modeling persons wearing PFDs in waves.

Table 1 presents an overview of the participants involved in this research project over the past three years along with points of contact.

Table 1 - PFD Research Participants

Wright-Patterson Air Force Base Vulnerability Assessment Branch Dr. Kaleps ATB Proj. Mgr. - Dr. Obergefell Manikin Lab. Proj. Mgr. - Capt Schultz	**U.S. Coast Guard Headquarters Lifesaving & Fire Safety Standards (G-MSE)** Staff Engineer - Mr. Wehr	**Transport Canada Ship Safety Administration** Proj. Mgr. - Mr. Gareau
Vector Research, Inc. (Developed SWIMs original skins)	**U.S. Coast Guard Research & Development Center** Proj. Mgr. - Mr. Macesker	**Melville Shipping Ltd.** (Conducted various sensitivity and SWIM volumetric studies)
Systems Research Laboratories, Inc. (Awarded the original contract for design and construction of SWIM)	**General Engineering & Systems Analysis Company, Inc.** WAFAC & SWIMVU Developer - Mr. Rangaraajan	**Institute for Marine Dynamics** (Conducted validation experiments with ellipsoids)
EME, Inc (designed and constructed the data acquisition system in SWIM)		

3.0 WATER FORCES ANALYSIS CAPABILITY (WAFAC)

3.1 WAFAC Theory Overview

3.1.1 Model Description

The WAFAC model predicts human body response to water forces corresponding to still water or to wave conditions and can be used to examine the effects on body motion with a PFD attached. The WAFAC model employs linear wave theory to determine the forces on a submerged body. The forces involved include buoyancy, wave excitation effects, added-mass, damping, drag, and lift. Incident waves are defined by the wave length, wave amplitude, and phase angle. The model predicts gross body motion as well as individual segment accelerations, velocities, and displacements. Buoyancy, added-mass, drag, lift, and wave forces are calculated in user-defined reference frames.

3.1.2 Model Information

Three items of information are required to describe the motion of a person attached to a PFD floating in waves. The first is a description of the water environment which includes a description of the water surface and water forces acting on the person. The second is a complete description of the person floating in the water. The person must be described by a system of linked segments with an accurate characterization of the properties of the individual segments. These properties include segment contour geometry, segment locations, mass-moment-of-inertia, center of mass, and joint torque definitions. The third item required is an adequate description of the PFD attached to the individual.

3.1.3 General Approach

The solution of freely floating bodies in surface waves is difficult. The WAFAC model approach is to employ potential flow theory. It is stated in Reference (5) that *the maneuvering problem generally involves separation and lifting effects, whereas the motions of bodies in waves are not as significantly affected by viscosity or vorticity.* However, a purely non-viscous treatment would not adequately describe the viscous nature of the local boundary layer. Therefore, the WAFAC model presently employs a viscous treatment in the form of drag and lift effects.

Developing a useful model for this application is an iterative process. It includes an empirical approach where at first coefficient values for damping, added mass, and lift will be assumed from simple shape experiments and computer sensitivity studies. Experimental data on individual and linked segments followed by whole body tests will need to be collected.

There is some level of risk in the selection of an initial model. As the experimental database increases it may be determined that the present WAFAC modeling approach is not optimum. Other models or techniques may need to be investigated but can be applied to the same framework developed to function with the ATB program. A full size instrumented flotation manikin is also basic to conducting correlation experiments to fine tune and to define the range of practical usefulness of the analytical model.

3.1.4 Wave Model

The mathematical description of water waves is complex and any attempts at classifying them is in the form of idealized conditions. In developing a simulation capability, a two dimensional wave motion is adopted. Although, a two dimensional wave can only be approximated in a laboratory environment, it represents a starting point in developing a rough water capability. Water wave theories can be generally classified as either "small amplitude" or "long wave" theories. Long wave theory addresses non-linear breaking waves. Wave breaking is a complex phenomenon which can seen as breakers at a beach or as white caps at sea. The WAFAC model uses small amplitude wave theory.

A complete description of wave behavior will involve both its surface form and fluid motion beneath the wave. In the case of a person, that is not moving through the water along the surface, the dominant forces will likely be related to the water particle accelerations rather than drag forces. The WAFAC model uses linear wave or small amplitude wave theory as the first approximation to describing wave characteristics. The model assumes that water flow will be incompressible, invisid, and irrotational so that the velocity field can be represented as the gradient of a scalar function ϕ or the velocity potential. By this, it is meant that the description of flow is outside the boundary layer where the flow is frictionless. Both the kinematics and dynamic boundary conditions are used to define the free-water surface. These can be combined to yield a single boundary condition for the velocity potential, ϕ . This equation is ,

$$\frac{\partial \phi^2}{\partial t^2} - g\frac{\partial \phi}{\partial z} = 0 \; .$$

The simplest solution of the free surface condition is the two-dimensional plane sinusoidal progressive wave which can be described by its free-surface elevation, η , with wave amplitude, A, wave number, k, and wave frequency, ω as,

$$x,y,t \; = A\cos\left[k \; x\cos\beta + y\sin\beta \; - \omega t + \varepsilon\right].$$

Water depth, h, is defined by either being of finite depth or infinite depth. For a fluid depth that is infinite, i.e., $h \rightarrow \infty$, the velocity potential is given as,

$$\phi = \frac{gA}{\omega} e^{ky} \sin(kx - wt),$$

and for finite depth the velocity potential is,

$$\phi = \frac{gA}{w} \frac{\cosh k(y+h)}{\cosh kh} \sin(kx - wt)$$

The WAFAC model is presently limited to the use of up to ten regular waves to describe the free surface. The waves are uniquely defined by their wavelength, amplitude, phase angle, and wave direction.

3.1.5 Water Forces

The WAFAC model accounts for hydrostatic pressure, wave excitation, added mass, and drag and lift effects when calculating the water forces on the body. Buoyancy effects are due to fluid pressure acting on the body. Wave excitation effects create forces and moments that act on the body. Added mass represents the amount of fluid accelerated with the body. Drag on a sphere moving through the water will be subjected to friction and form drag. This model evaluates the wave excitation forces as a function of depth of the submerged object. Figure 1 illustrates the types of water forces considered.

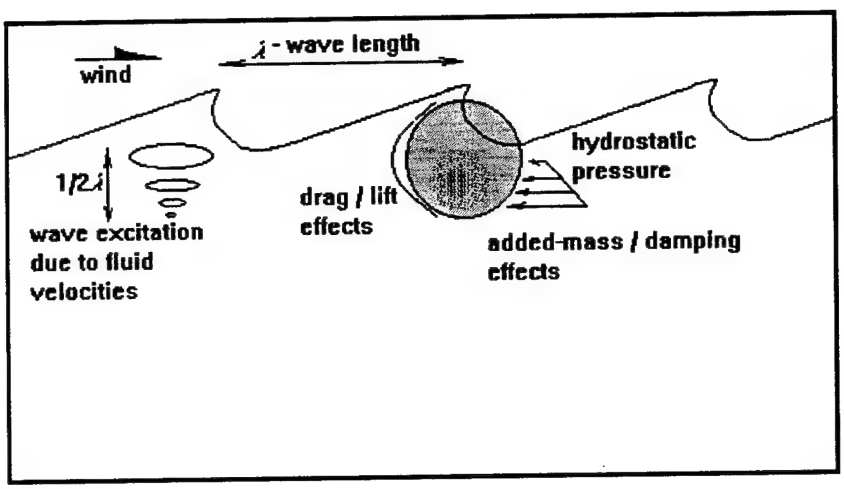


Figure 1. Water Forces Affecting a Floating Body

The computation of the total water force acting on a body is derived by Newman in Reference (5) and was the approach used in the WAFAC model. The total potential is,

$$\Phi(x,y,z,t) = \mathrm{Re}\{(\sum_{j=1}^{6} \xi_j \phi_j(x,y,z) + A\phi_A(x,y,z))e^{iwt}\}$$

The first term represents the velocity potential of the rigid body motion in the absence of waves and provides the description to the radiation problem. The second potential term represents the interaction of the body with the incident waves and provides the general description of the diffraction problem. This term can be further decomposed into diffraction, ϕ_o , and scattering, ϕ_7,, effects of the incident wave on a fixed body,

$$\phi_A = \phi_o + \phi_7$$

$\xi_j, j = 1-6$ represent the dependent body motions in heave, pitch, roll, yaw, surge, and sway. The forces and moments acting on a floating body are determined in Reference (6) by substituting the total potential into Bernoulli's equation,

$$p = -\rho(\frac{\partial\phi}{\partial t} + gy)$$

and then integrating the fluid pressure over the wetted surface yielding the following expressions,

$$\begin{bmatrix} F \\ M \end{bmatrix} = -\rho g \int_{S_B}\int \begin{bmatrix} n \\ rxn \end{bmatrix} y\,dS$$

$$-\rho \operatorname{Re} \sum_{j=1}^{6} iw\xi_j e^{iwt} \int_{S_B}\int \begin{bmatrix} n \\ rxn \end{bmatrix} \phi_j\,dS$$

$$-\rho \operatorname{Re} iwAe^{iwt} \int_{S_B}\int \begin{bmatrix} n \\ rxn \end{bmatrix} \phi_A\,dS$$

The first integral represents the hydrostatic contribution. The second integral represents added mass and damping contributions and the last integral is the exciting force or moment proportional to the incident wave amplitude. The velocity potential, ϕ_o, comes from the potentials for finite and infinite depth described previously. The frictional effects of drag and lift are computed as,

$$F_D = \frac{1}{2} C_D A_{proj} \rho V_{rel}^2$$

and,

$$F_L = \frac{1}{2} C_L \sin 2\alpha A_{proj} \rho V_{rel}^2$$

'α ' is the angle between the normal vector **n** and V_{rel}. C_D and C_L are the drag and lift coefficients, respectively.

The Final Report to the U.S. Air Force describes the water forces adaptation of the Articulated Total Body (ATB) Model Program and contains discussions sections on Theory, User Instructions, and Program Changes which describe the WAFAC capability (Reference (6)).

3.2 WAFAC Program Use Overview

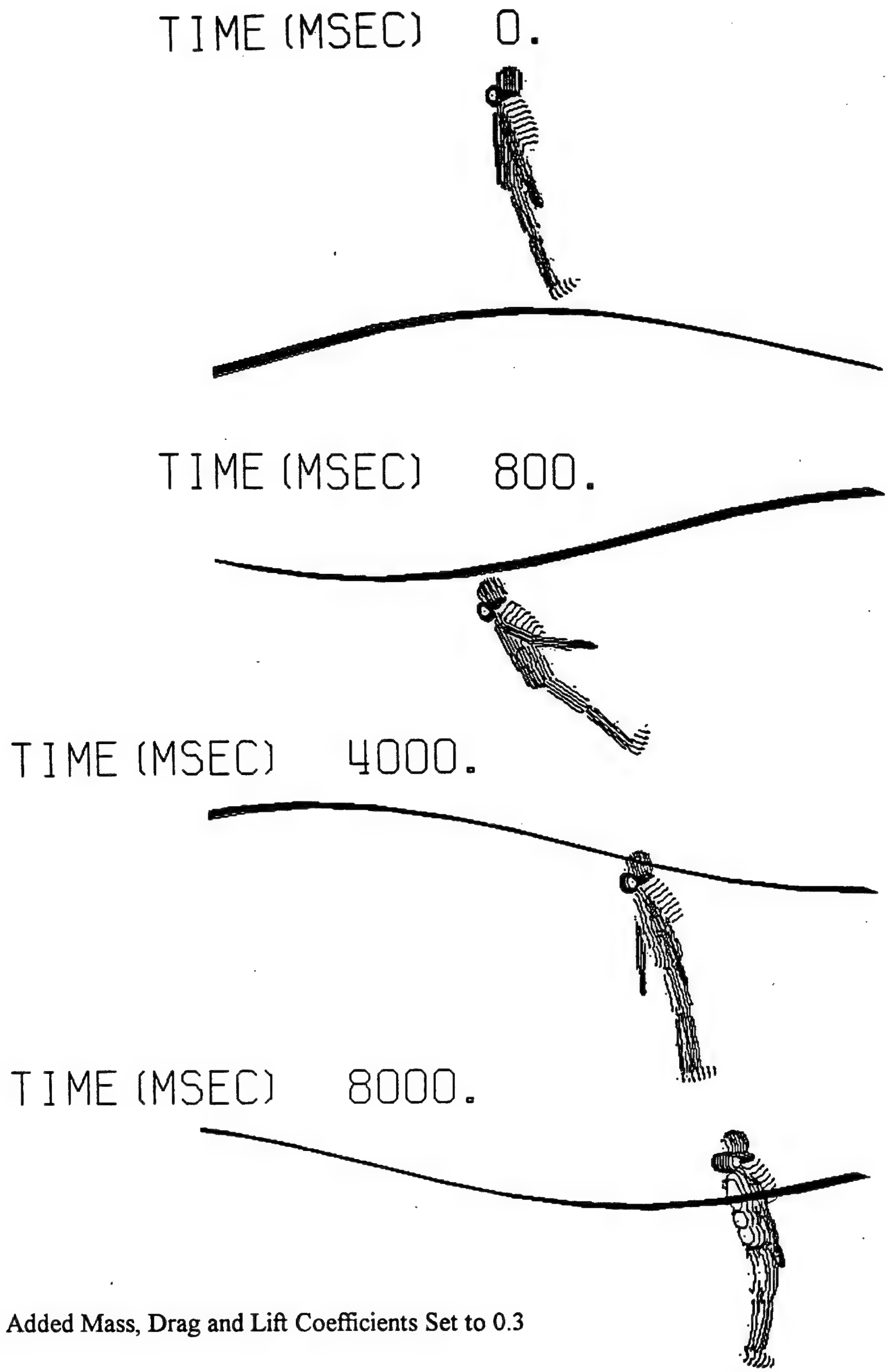
3.2.1 Program Output

The simulation software can be run with a 80386 processor personal computer as an executable. The user can define the wave characteristics such as wave length, height, phase and the initial starting conditions of the test subject. Simulations can also be run with simple geometric shapes. Figure 2 demonstrates the interaction of a manikin (Hybrid III) standard wearing a PFD in two regular waves out of phase. The manikin was initially dropped into the waves. The PFD was modeled with five ellipsoids. Figure 3 illustrates a couple of possible WAFAC output time histories associated with this simulation.

3.3 WAFAC Validation Efforts

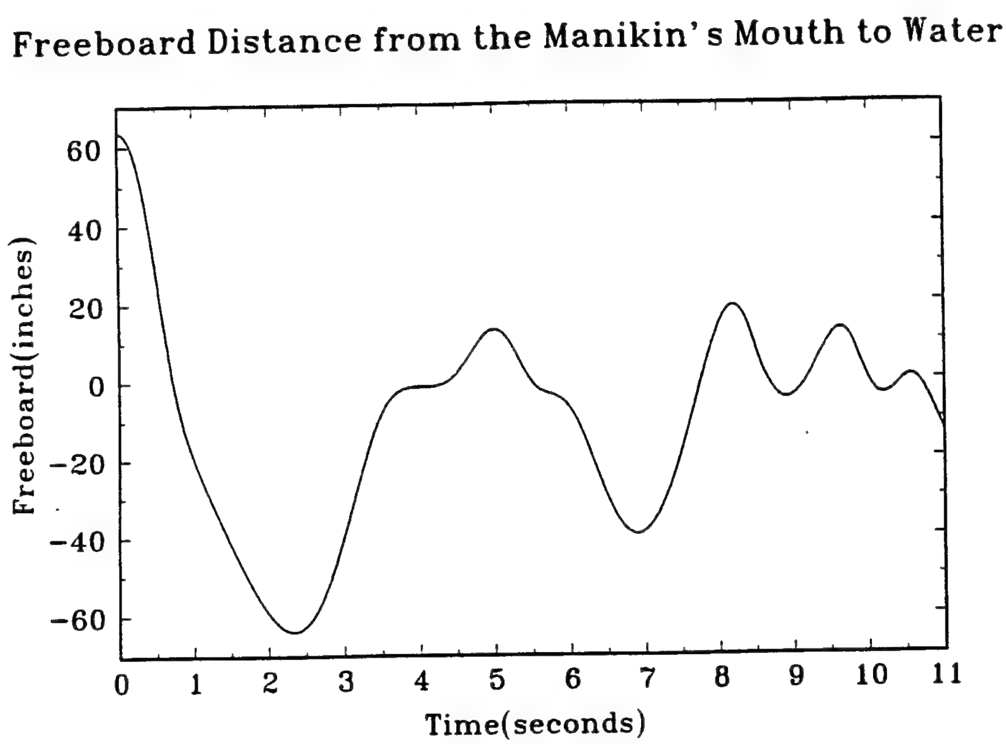
3.3.1 Ellipsoid Experiments

Physical experiments were performed by the Canadian National Research Council's Institute for Marine Dynamics (IMD) towing tank facilities in St. John's, Newfoundland. Several simple shapes were constructed to approximate the dimensions of the human head, arm, and torso segments. The shapes were constructed of high density foam and shaped by a 3-axis milling machine. Layers of fiberglass with an epoxy coating followed by a white gel coat were applied to the ellipsoid surfaces. Two sets of ellipsoids were constructed with specific gravity's of 0.5 and 0.95 (close to neutral buoyancy). Construction of the ellipsoids is described in detail in Reference (7). A test frame was custom designed for the trim dock of the towing tank for these experiments. This setup is illustrated in Figure 4. It was designed for drop and bottom release testing of ellipsoids. The procedures for releasing the ellipsoids are described in Reference (7). The displacement motion of the released ellipsoids were captured by video imaging followed by digital processing of the associated still frames. The resulting motions were documented in the form of vertical position versus time for all combination of high and low density segments. Drag coefficients were determined from the bottom release tests. At terminal velocity the weight, buoyancy, and drag forces were balanced. A least squares fit to the displacement time series allowed the estimation of the drag coefficient.



Note: Added Mass, Drag and Lift Coefficients Set to 0.3

Figure 2. Sample of PC WAFAC Capability with a Manikin



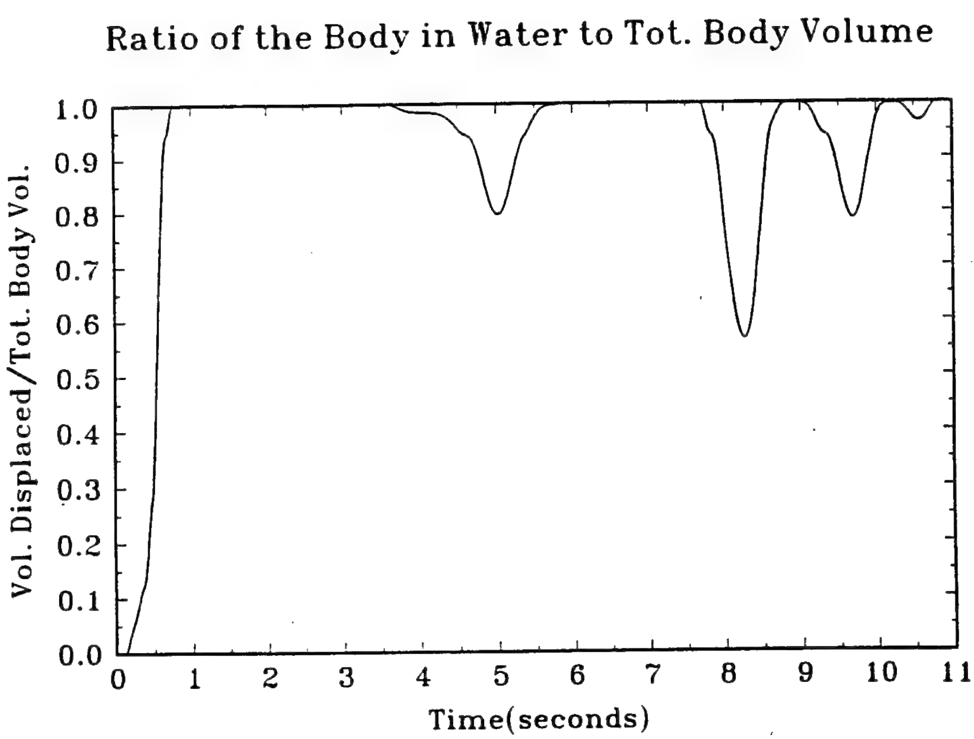


Figure 3. Samples of Time History Output from WAFAC Simulation

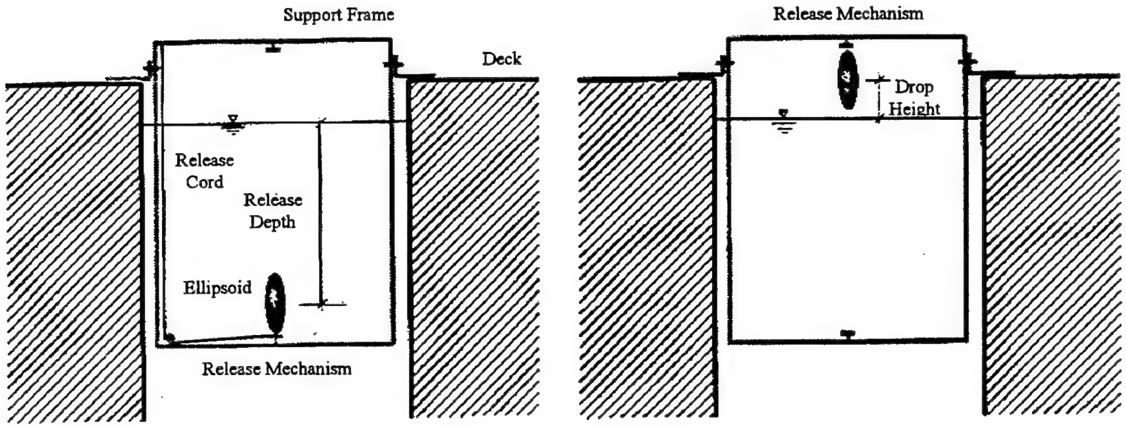


Figure 4. IMD Test Setup

Experimental data were also collected on various combinations of hinged segments beneath the water's surface. These data, after analysis, will contribute to an understanding of the influence of rotational hydrodynamic effects and the sensitivity of segment motion when partially blocked by another.

A series of computer simulations were performed to simulate some of the tests conducted by IMD using the WAFAC computer model and SWIMVU (Reference (8)). This effort represents the first step in a systematic validation effort to compare the predictions from the WAFAC model with those from the controlled IMD experiments.

A postprocessor called SWIMVU was developed based on the DYNAMAN postprocessor to allow the user to look at the plots related to the various components of the hydrodynamic forces. SWIMVU was used to import the IMD experimental data for comparison to the WAFAC simulation. Comparisons were based on experimentally derived coefficients and then modified coefficients. Figure 5 presents an overlay of the experimental and analytical time motion history of a sphere with specific gravity close to that of water released from 0.91 meters below the water's surface. Using published values for the hydrodynamic coefficients,

Added Mass:	0.5
Drag:	0.61
Wave Damping:	$a_o = 0.24$
	$a_1 = 0.53$,

good correlation is achieved. The wave damping coefficients were estimated for an ellipsoid (Reference (9)).

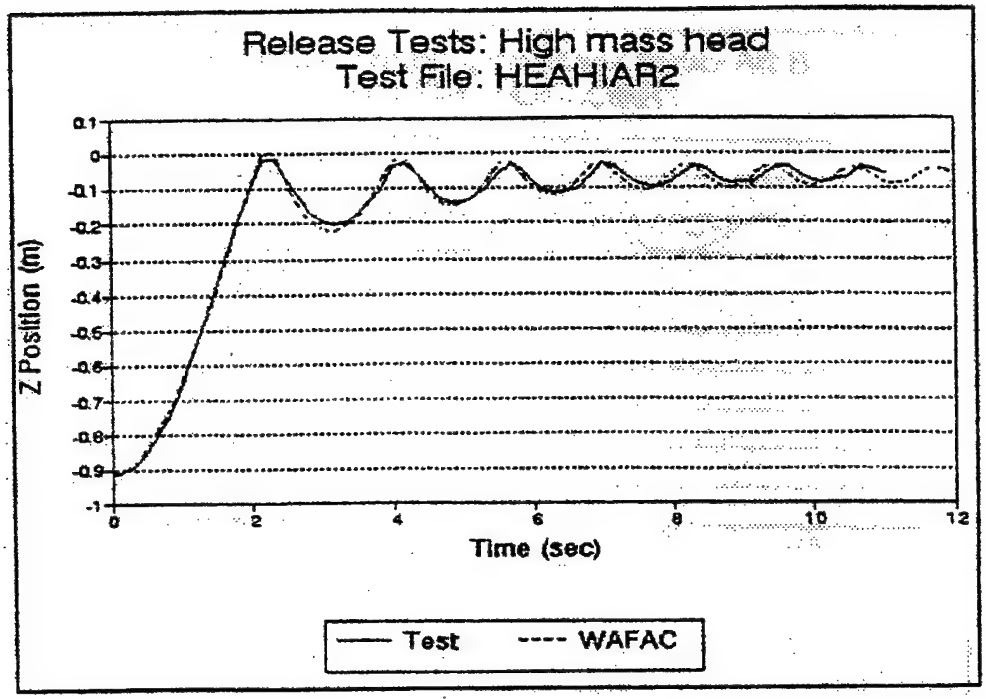


Figure 5. High Density Sphere Released from 0.91 m

It can be seen in Figure 6 that the correlation is not quite as good when the sphere is released closer to the surface. In this instance, the disparity is not obvious but may be related to the higher position from which the sphere was released, causing a difference in the wave making contribution. Figure 7 demonstrates a time series comparison of the same sphere attached to a hinge and released from an initial angle of 30 degrees. The correlation improves when the drag coefficient is increased in Figure 8.

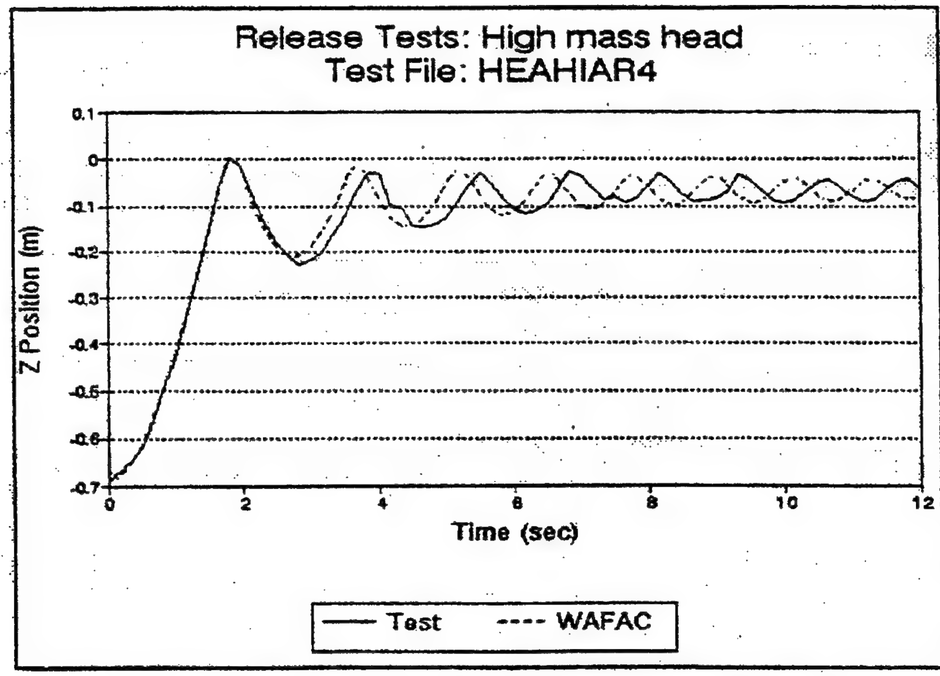


Figure 6. High Density Sphere Released from 0.68 m

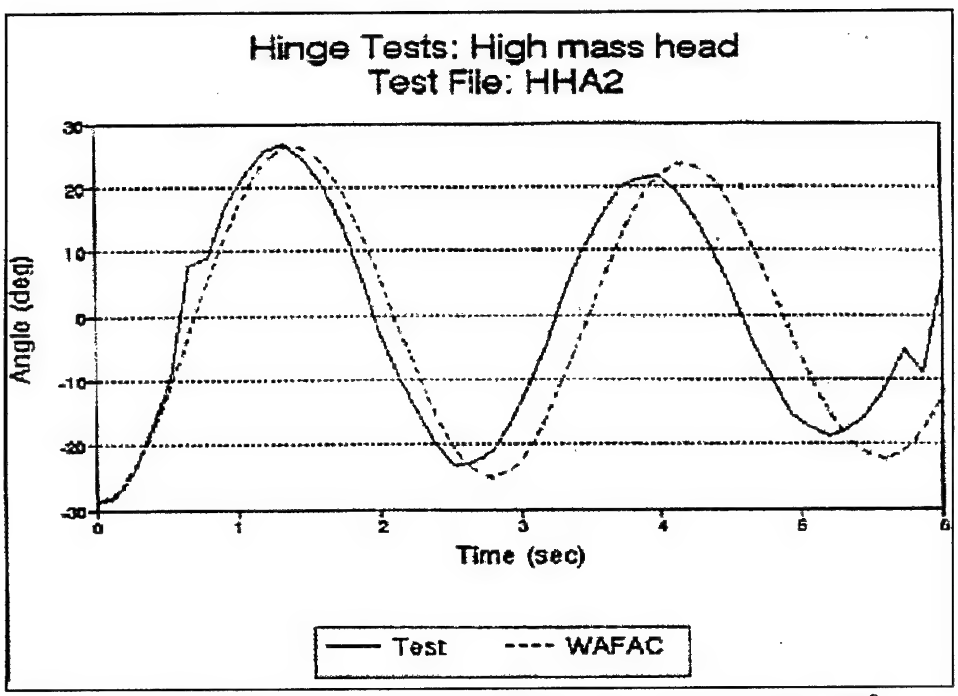


Figure 7. High Density Sphere Hinge Test (initial angle=29°, drag=0.6, added mass=0.5)

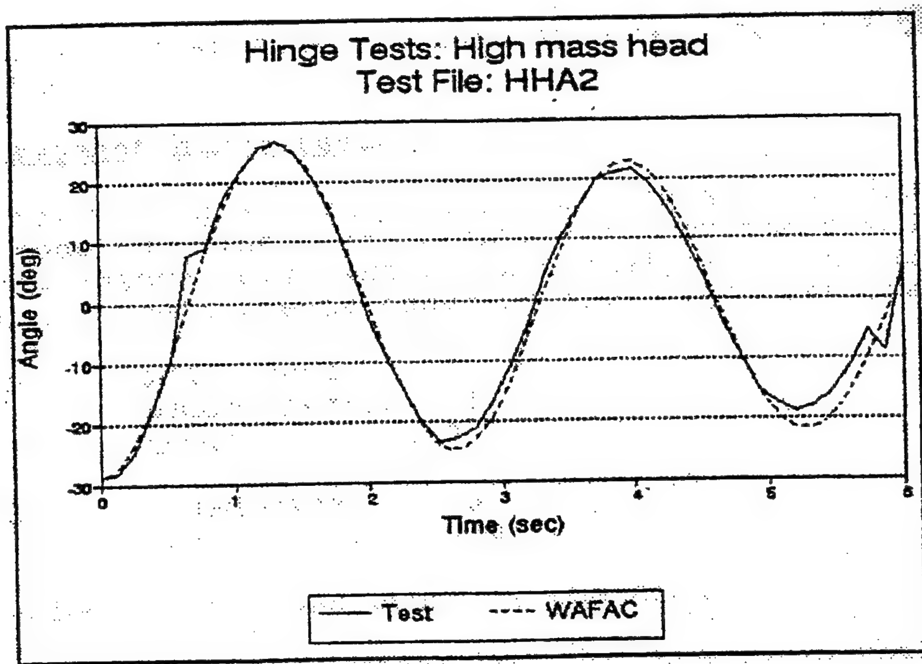


Figure 8. High Density Sphere Hinge Test (initial angle=29°, drag=2.0, added mass=0.5)

This initial work with the different ellipsoid shapes has demonstrated potential for full-body validation of WAFAC. There was good agreement on the time required to reach the surface and amplitude of oscillations at the surface. The predictions of the periods for decayed oscillations were not quite as good, i.e., the WAFAC model predicted smaller periods. It was suggested by GESAC, Inc. that wave damping coefficients may need to be modified as a function of time (Reference (8)).

In general, the motions of the more complicated linked segment hinge tests were predicted fairly well, but the motions over a small time scale showed differences. This can be interpreted, assuming that time spent by the head above the waters surface is a performance criterion, that over a long enough period of time the average height above the waters surface would be predicted accurately. However, it could not be predicted very well whether its above the surface within a specified time range.

A study performed by Melville Shipping, Ltd. included some limited sensitivity analysis of hydrodynamic factors in modeling an ellipsoid (Reference (10). The conclusions were that varying the added mass and damping coefficients had minimal effect on motion of an ellipsoid released just below the water's surface but that changing the specific density affects the motion greatly. Their study also pointed out that because the majority of a person wearing a PFD is usually submerged, wave damping effects may not be as important as first thought.

There are numerous sources of conflict in developing a 100% reliable prediction capability with the WAFAC program. For example, the ellipsoid segments in the ATB program overlap at the joints causing some double accounting of buoyancy; SWIM has free-flooding joints which may complicate the accounting for this buoyancy in the model; and the shape of SWIM's segments are not true ellipsoids like those used in the ATB program. It is anticipated that the ATB WAFAC calculations will be approximations that may only provide reliable predictions within a certain margin. Predictions associated with automobile crash test modeling within 10% are considered good. The level of modeling difficulty for this application will be revealed when full-body motion response data captured with SWIM is compared to a WAFAC simulation of similar initial conditions.

4.0 SEA WATER INSTRUMENTED MANIKIN (SWIM)

4.1 SWIM Performance Requirements

Performance requirements for SWIM were developed in 1992 and were based on recommendations outlined in Reference (11). The sponsoring agencies were the U.S. Coast Guard and Transport Canada in accordance with the United States Department of Transportation/Transport Canada Joint Research Project Agreement Number 6 for the Performance Research of Personal Flotation Devices. Performance requirements addressed materials, maintenance, watertight integrity, anthropometric data, sensors, instrumentation, and required special features.

4.1.1 SWIM Anthropometric Requirements

The anthropomorphic performance requirements developed were for a 50th percentile midsize male and included detailed dimensional, inertial, and joint data. The dimensional data consisted of a number of traditional body anthropometric measurements and locations of joint centers. The inertial properties were specified for each body segment and included the mass, center of mass, magnitudes of the principal moments of inertia, and the orientation of the principal axes. The center of mass locations and orientation of the principal axes for each segment were specified with respect to a segment mechanical axis system, a coordinate system aligned with the long bone axis and joint axis of that segment. All of the anthropomorphic performance specifications were based on the characteristics developed by the U.S. Air Force (Reference (11)).

The number of segments deemed necessary to replicate a floating person was 17. They are:

1. Head
2. Neck
3. Thorax
4. Abdomen
5. Pelvis
6. Right Upper Arm

7. Left Upper Arm
8. Right Forearm
9. Left Forearm
10. Right Hand
11. Left Hand
12. Right Thigh
13. Left Thigh
14. Right Calf
15. Left Calf
16. Right Foot
17. Left Foot

The segment weights, center of mass locations, and principal moments of inertia are presented in detail in Reference (11). It was required that the manikin and segment surface shapes conform to the corresponding shape for a mid-size male. The guidelines for the manikin shapes were derived from Reference (12). The shape data were determined through stereophotometric methods for mapping 3D surfaces. Segment buoyancy variability was required for the following segments:

thorax	forearms
abdomen	thighs
pelvis	calves
upper arms	

For any buoyancy adjustments made to the segments, the buoyancy change would have to be evenly distributed within the segment space about the segment longbone. The thorax requirements were to have expandable air volumes representative of a mid-size male. Joint resistance requirements were to reflect an unconscious PFD user, and an adjustable joint resistance capability was required to simulate an appropriate muscular joint resistance for each articulated joint. Provisions were required to the joint design for future additions of coil springs which, when loaded, would return the segments to an adjustable pre-set position.

During the design stage there was some debate over the chest design. The performance specifications called for an expandable air volume for the thorax with a buoyancy adjustment range of zero to ten pounds. The original contractor design consisted of a fixed and fillable air space which only provided a pseudo-variable buoyancy by adjusting the amount of mass in the thorax cavity. The Coast Guard sponsors chose a more realistic representation of the human thorax expansion. Retaining a constant thorax mass and expanding the thorax volume was adopted. It was believed that this was more likely to be accepted by industry as a standard. The manikin was required to have both the expandable chest and built-in variable ballast to account for future instrumentation weight growth.

4.1.2 SWIM Instrumentation Requirements

The U.S. Coast Guard and Transport Canada have only a qualitative knowledge of what the important measures of performance might be for a person wearing a lifejacket in rough water. Therefore, sufficient instrumentation was needed to address a spectrum of possible measurements with this manikin. The development of future follow-on manikins to be used as standards, after SWIM is validated, will not require the level of instrumentation sophistication as in SWIM. This would greatly reduce the construction cost.

The sensors required included a six degree-of-freedom (6-DOF) measurement system, twenty joint angular position sensors, and four pressure attitude sensors. The 6-DOF sensors were to be located in the chest cavity and measure heave, pitch, roll, yaw, surge, and sway. The joint angular position sensors were required to measure the following:

- neck extension
- neck flexion
- neck lateral flexion
- shoulder flexion
- shoulder extension
- shoulder abduction in the transverse and coronal plane
- elbow flexion
- hip flexion
- hip abduction
- knee voluntary flexion

The pressure attitude sensors were required to be located near the armpits and buttocks so that average readings could be made about the mid-sagittal and transverse plane.

A special feature to record the amount of water ingested from face splashes or immersions of the manikin's head were needed. The collected water would need to be removed for post-testing volumetric analysis.

An on-board 32 channel data acquisition system was required to collect all of the sensor data. A special safety feature was required to ensure that the manikin would resurface if buoyancy difficulties arose. Therefore, performance requirements include the integration of a mechanical hydrostatic CO_2 cartridge which was to be completely independent of the manikin's electrical and electronic systems.

4.2 SWIM Design Overview

Figure 9 presents a SWIM manikin schematic overview. A complete listing of fabrication drawings can be found in the Air Force's draft TOR (Technical Operating Report) in Reference (13). Figures 10 through 12 show front, side, and back views of the assembled manikin, respectively. Figures 13 through 20 show various subassemblies (photos and schematics) of the SWIM manikin. The TOR provides details on the subassembly interconnections and on SWIM's overall system description, operation, handling, and maintenance guidelines.

A summary discussion of SWIM features follows.

Anthropometry. Anthropometric characteristics of the mid-sized male SWIM were generated from multiple regressions on stature and overall body weight of the general population. These data provided information on body component inertial properties, e.g., segment mass, moments of inertia, and centers of mass, joint ranges of motion and friction characteristics, and body segment contours from stereophotometric data analysis. The body characteristics are similar to the Hybrid manikin used in automobile crash testing. SWIM has a stature of 69 inches and weight of 169 lb. with 17 body segments.

Construction Materials. The skeletal structure of SWIM consists of stainless steel, aluminum, high molecular weight polyethelene, and delrin. The skin molds are vinyl with closed cell foam beneath the skin.

Controlled Buoyancy of Body Components. The original performance specifications called for pressurized air to be inserted into body components to expand the vinyl skin thereby increasing the volume of the body segment while maintaining a constant weight. Several skin segment prototypes were fabricated by two different vendors with open cell foam encapsulated in vinyl with an inflation valve and with closed cell foam without an inflation valve. The new skin segments were tested by inflating them and immediately demonstrated delamination and bubbling on the vinyl from the internal foam. The inflatable skin segment concept, i.e., for fine tuning of individual segment buoyancy, was abandoned because a uniform density decrease could not be achieved.

An alternative and simpler approach was chosen to address the fine tuning of buoyancy for individual skin segments. The alternative approach employs through holes, approximately one inch in diameter, at strategic locations on each skin segment do not appreciably affect the individual segments inertial properties. A cylindrical space was created for a slug of either closed cell foam, same as the skin internal, or lead for increasing the density of a particular segment. Although, this is an opposite approach to that of inflating the individual segments, it can achieve the same effect, i.e., fine tuning, provided that the inherent density of each segment is 5% positively buoyant.

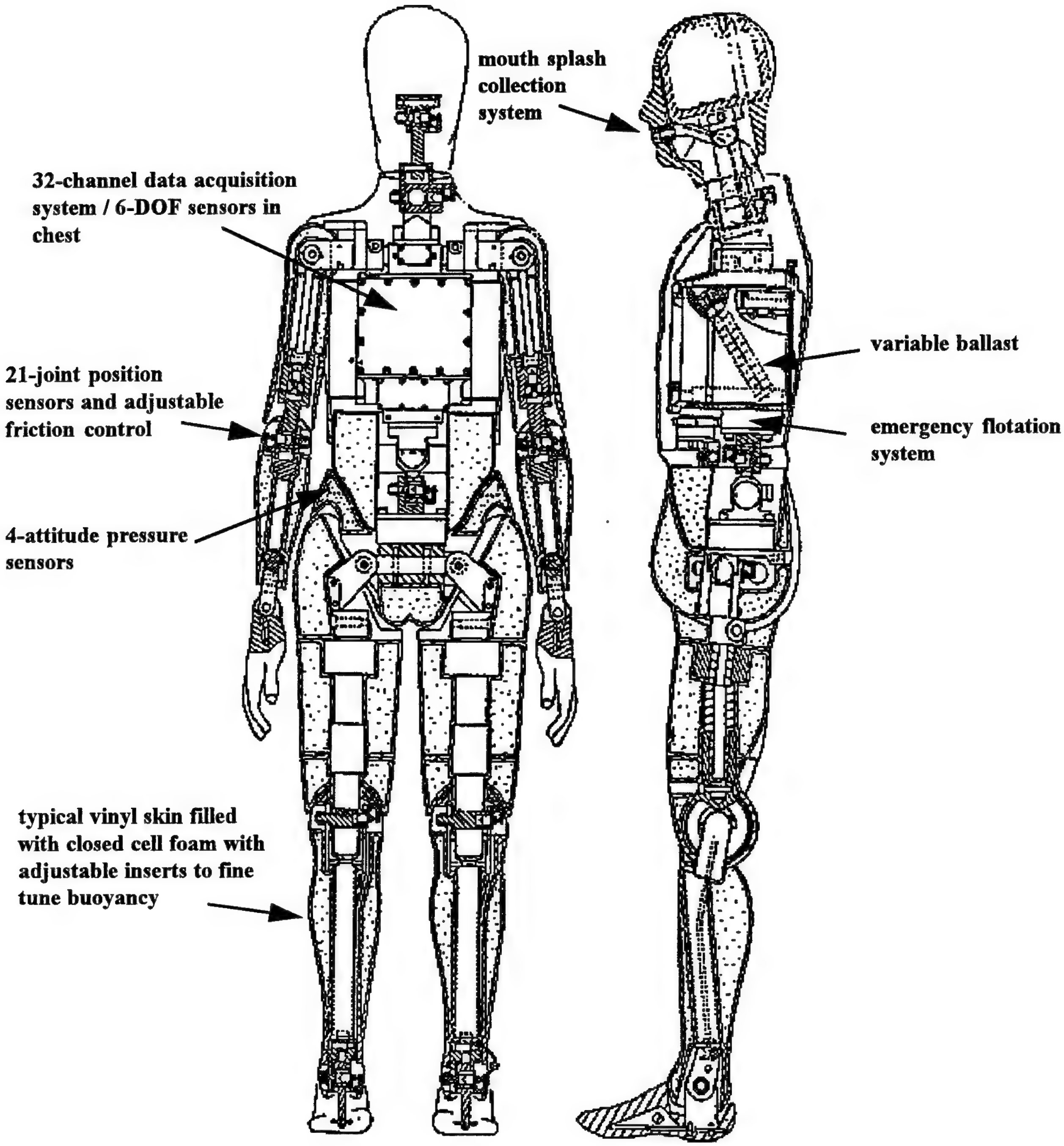


Figure 9. Flotation Manikin Schematic Overview

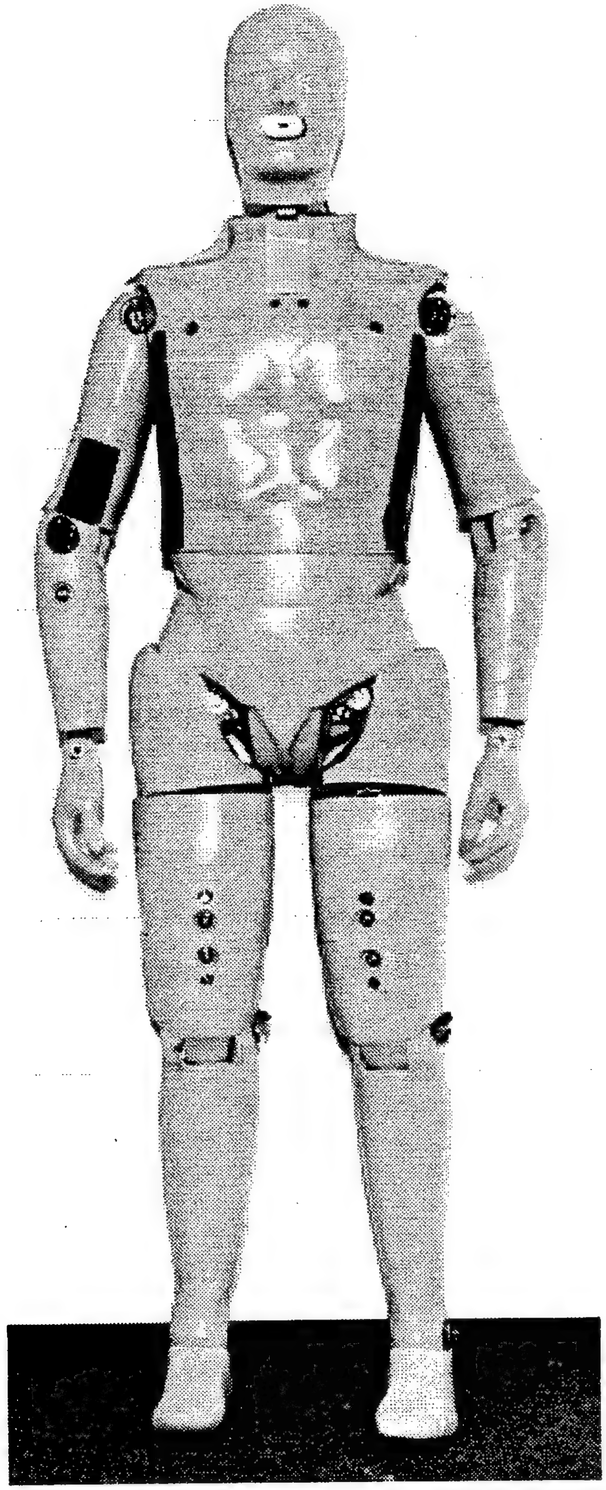


Figure 10. Flotation Manikin, Front View

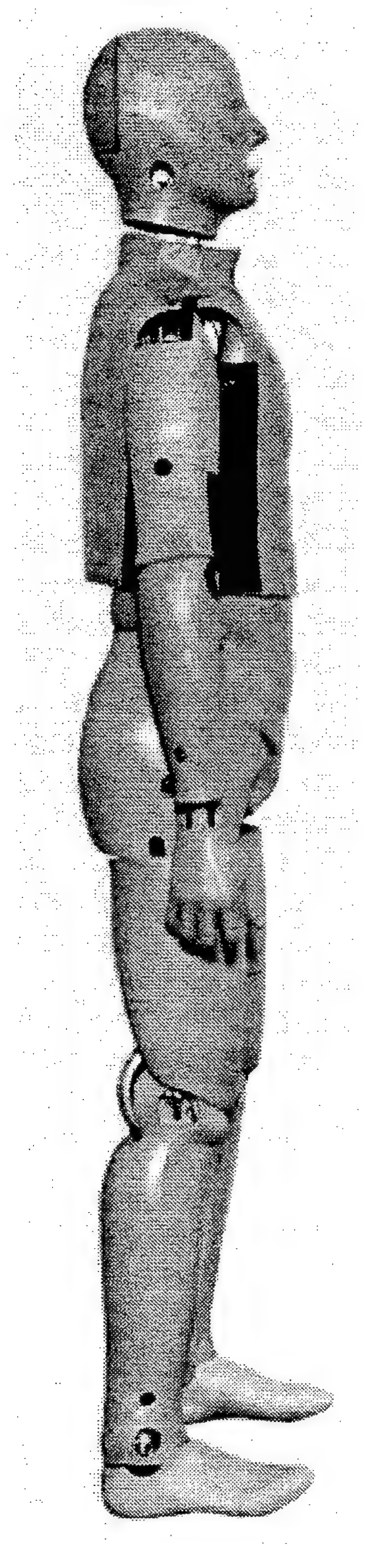


Figure 11. Flotation Manikin, Side View

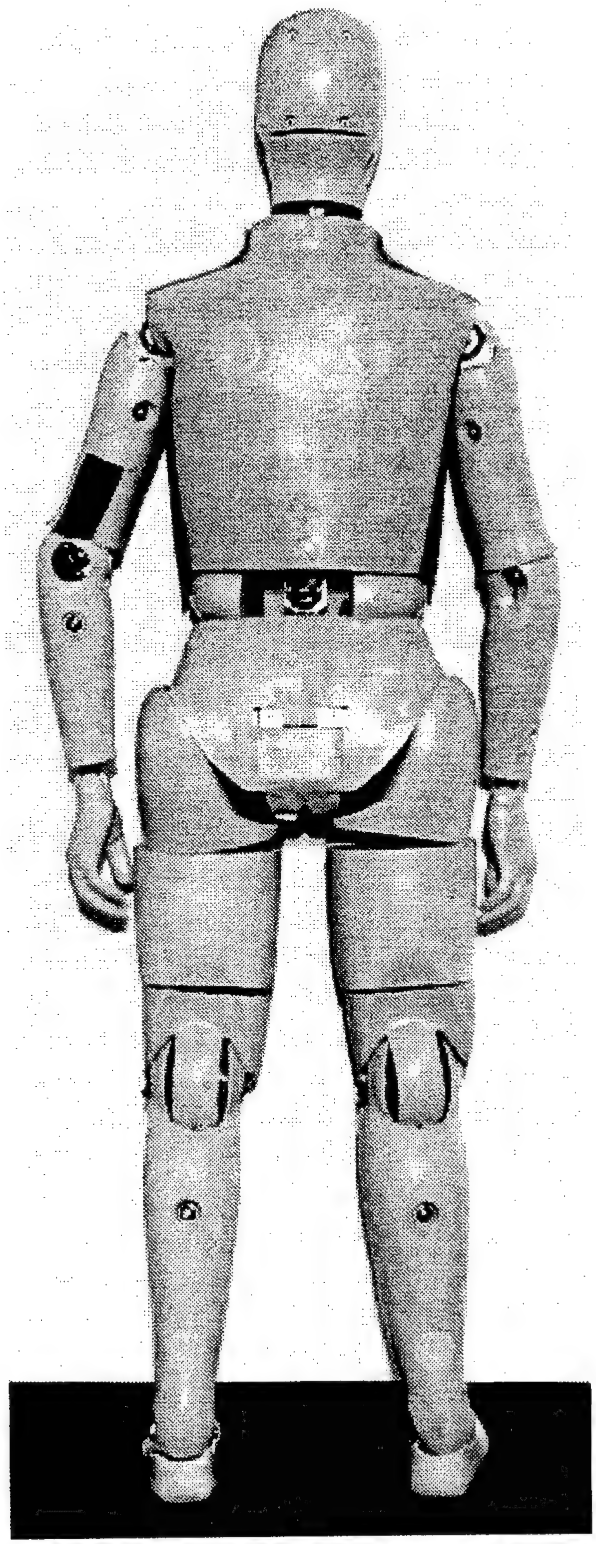


Figure 12. Flotation Manikin, Rear View

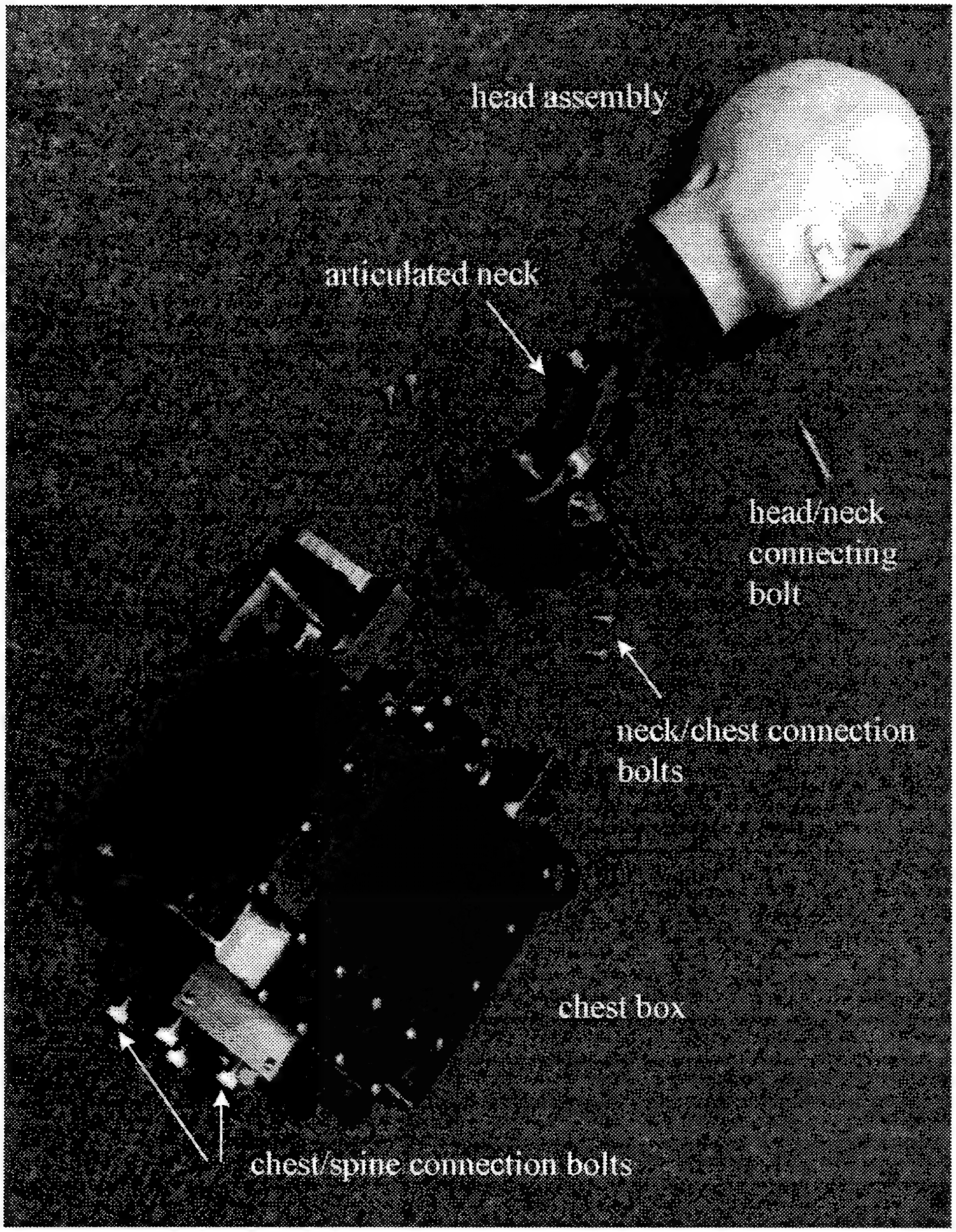


Figure 13. Head, Neck and Chest Box

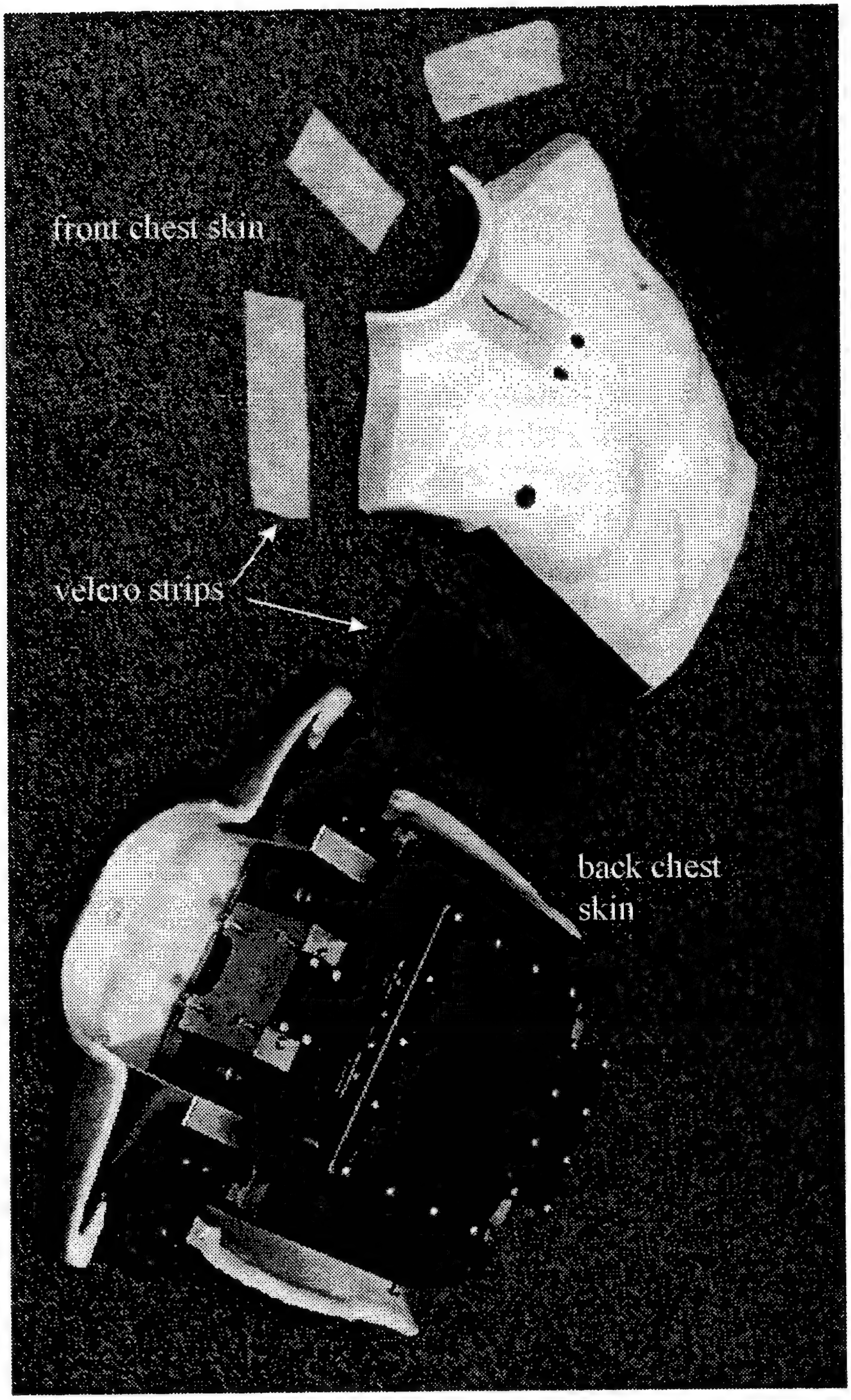


Figure 14. Chest Skins

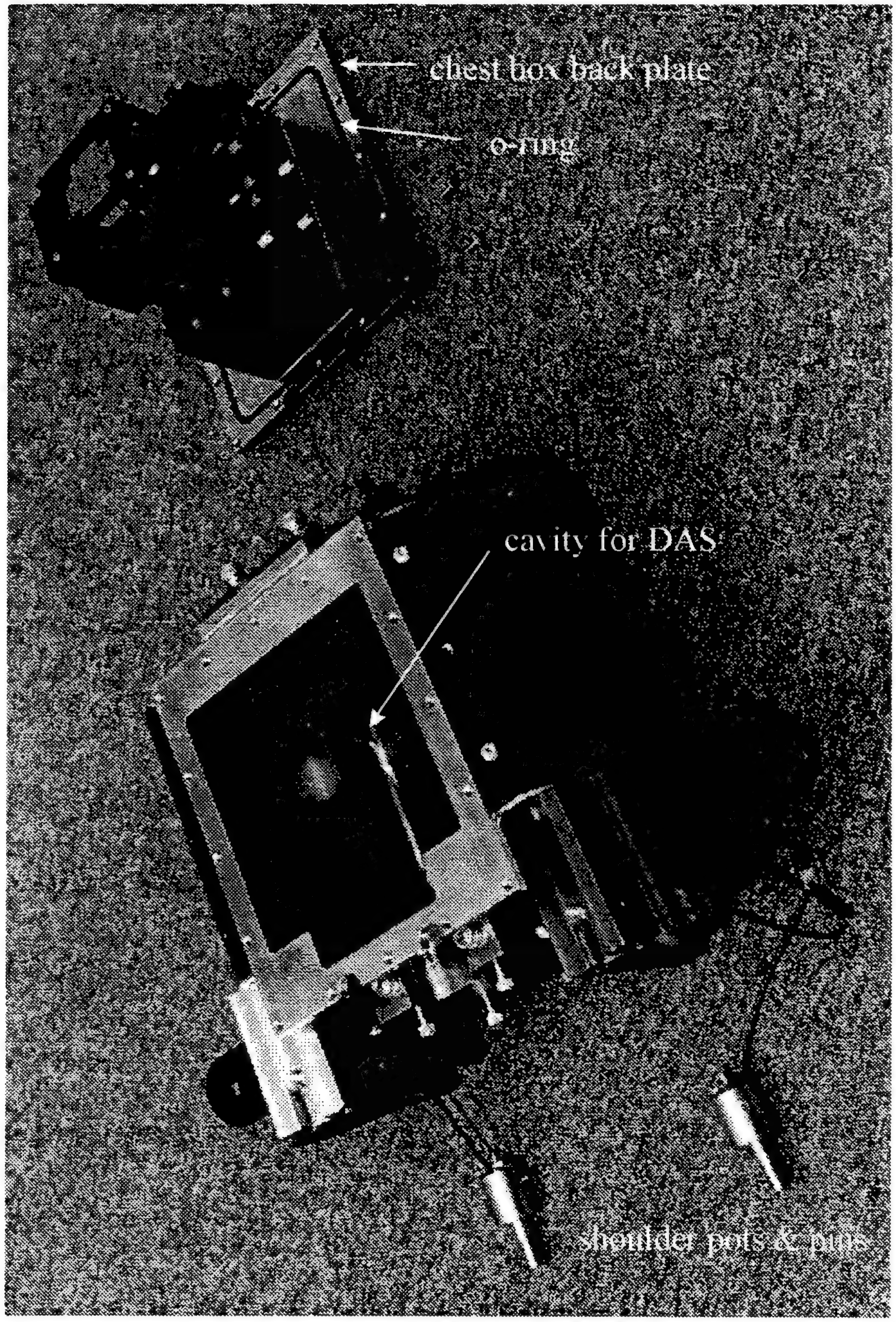


Figure 15. Chest Box (Rear View - Back Plate Removed)

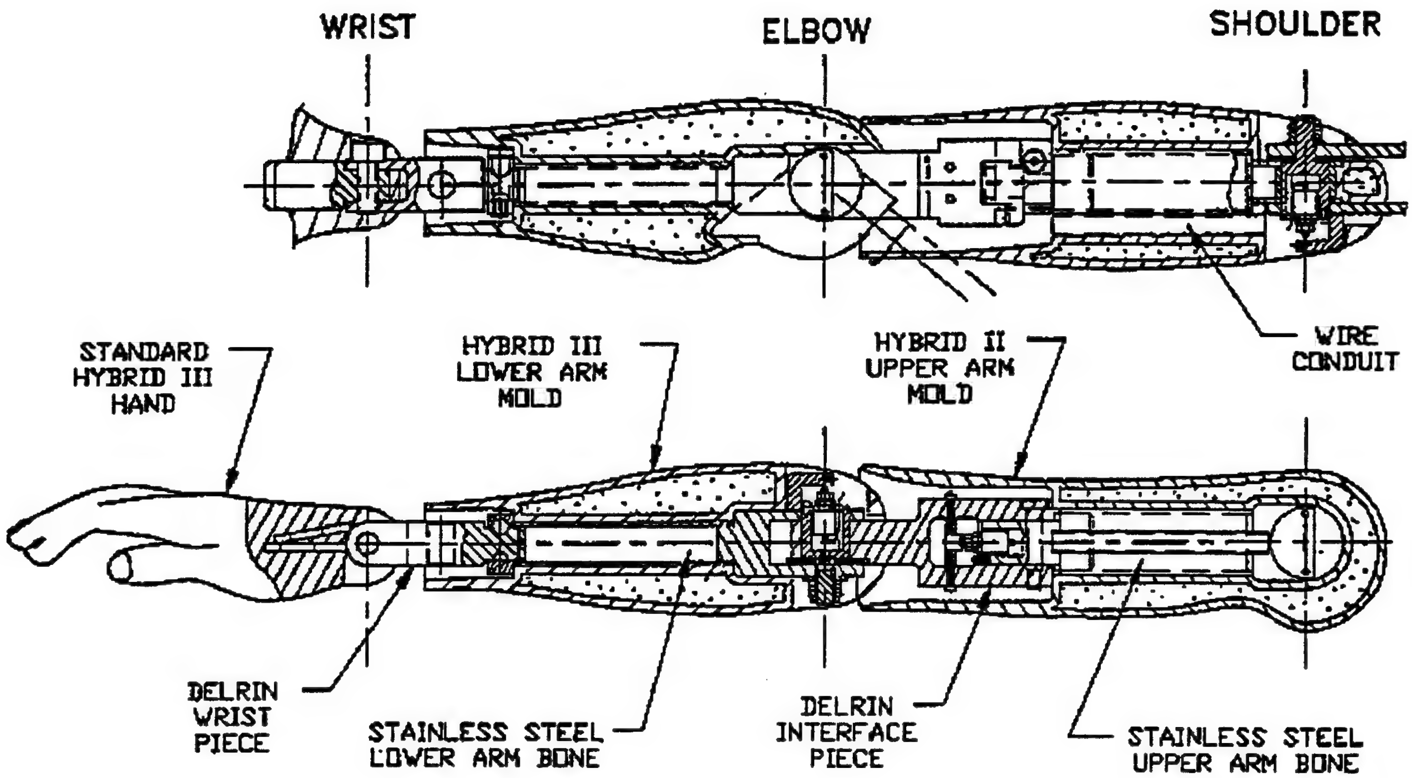


Figure 16. Flotation Manikin Arm Schematic Overview

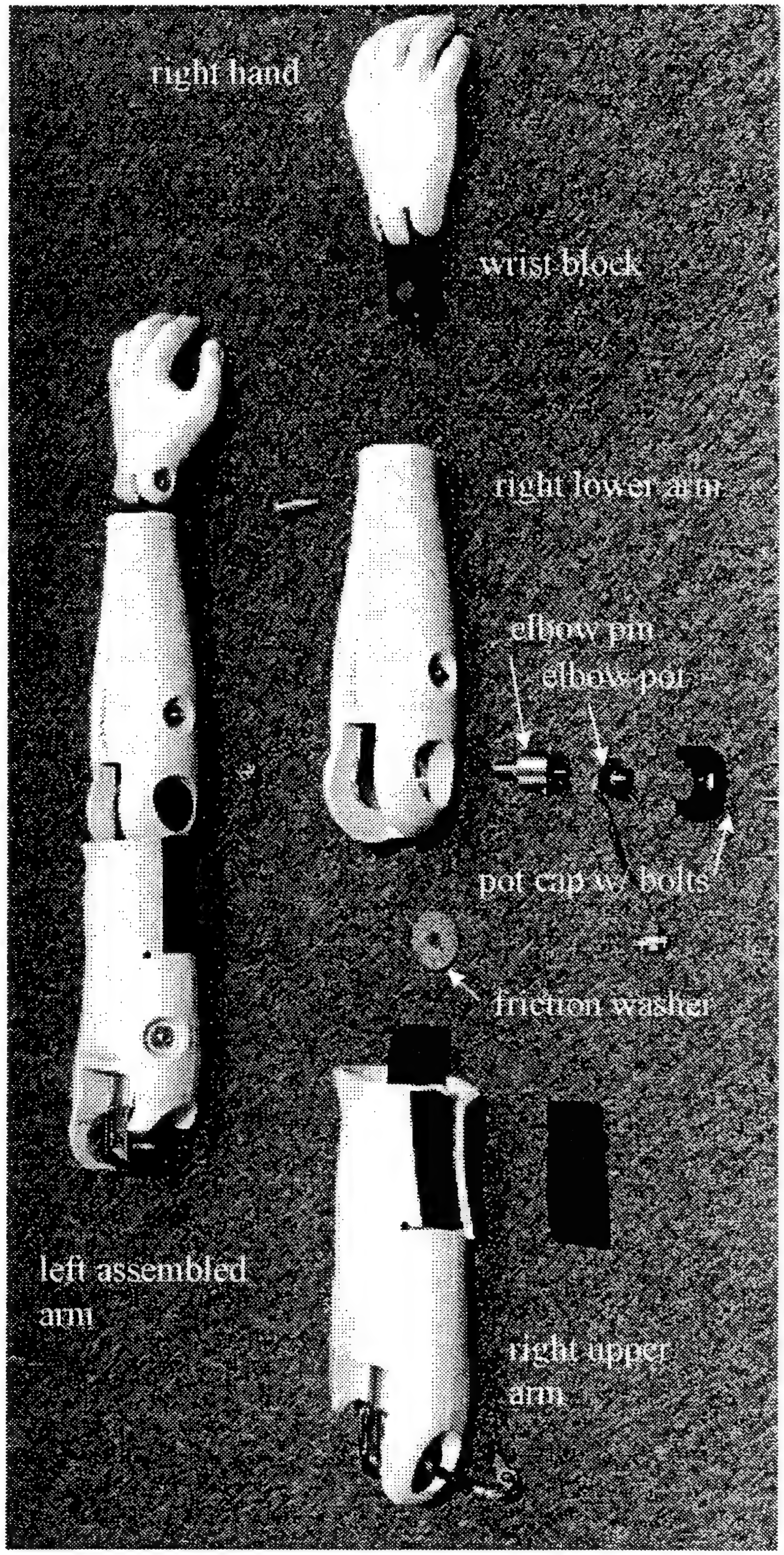


Figure 17. Arm Segment Connections

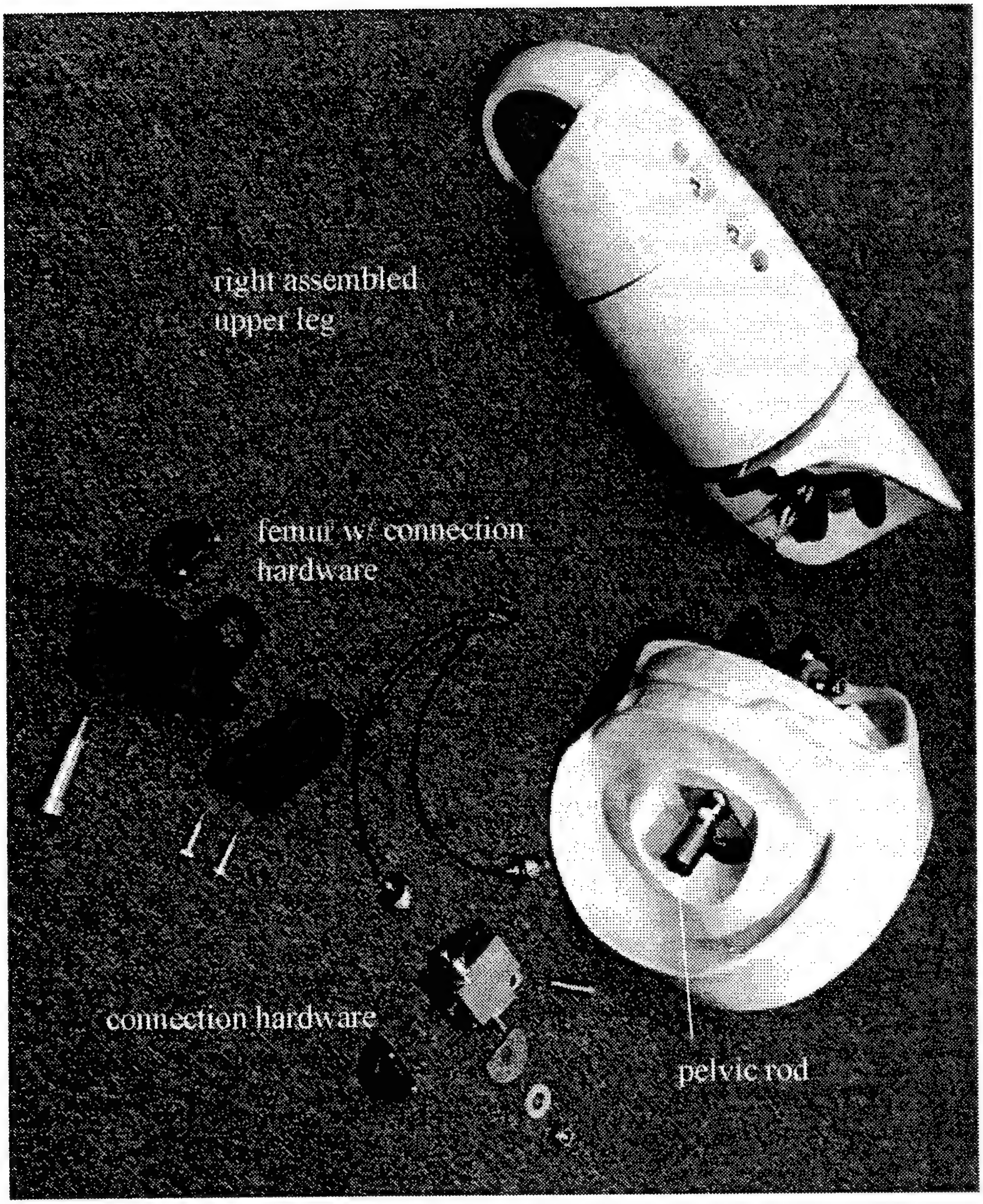


Figure 18. Pelvic to Upper Leg Connection

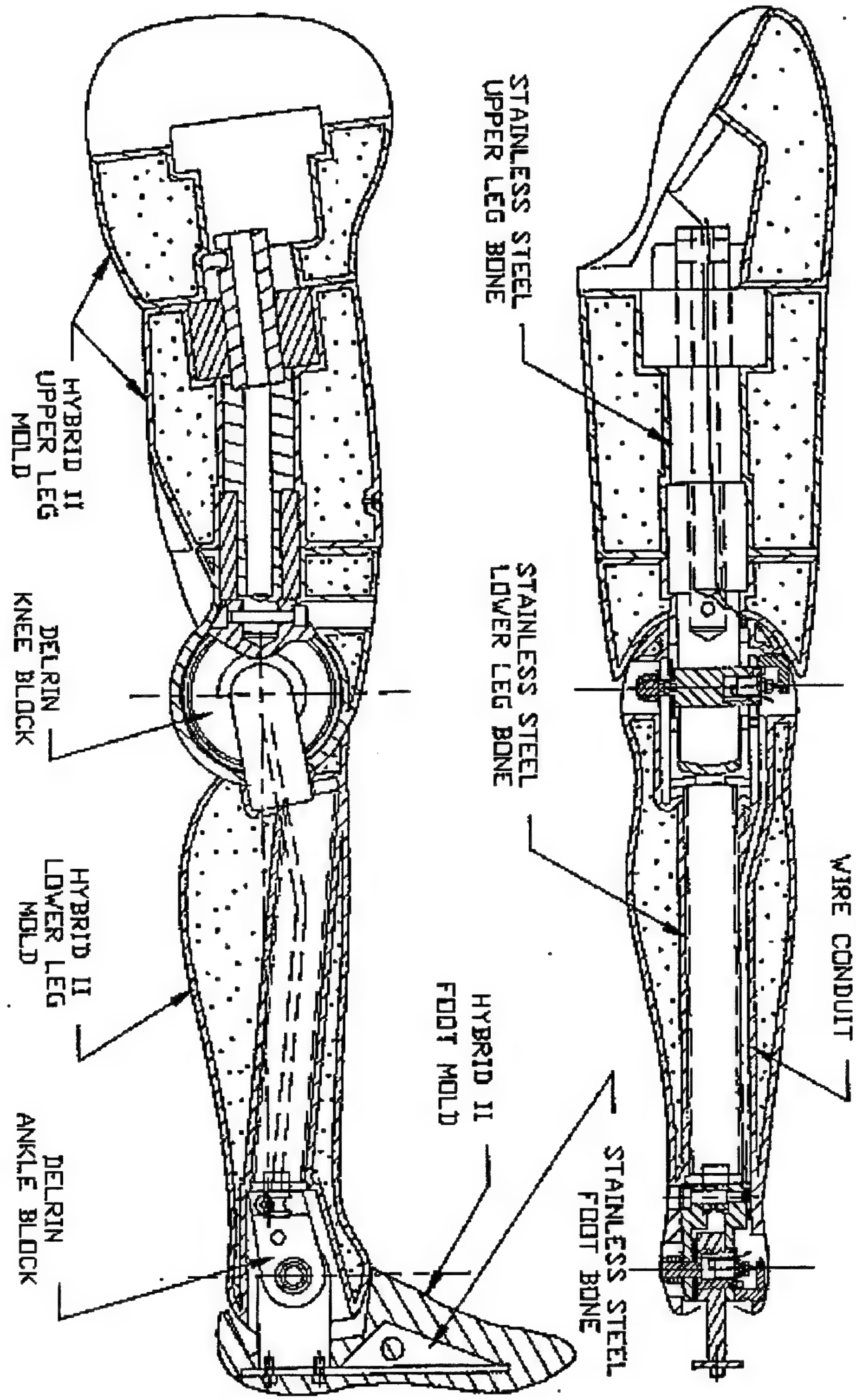


Figure 19. Flotation Manikin Leg Schematic Overview

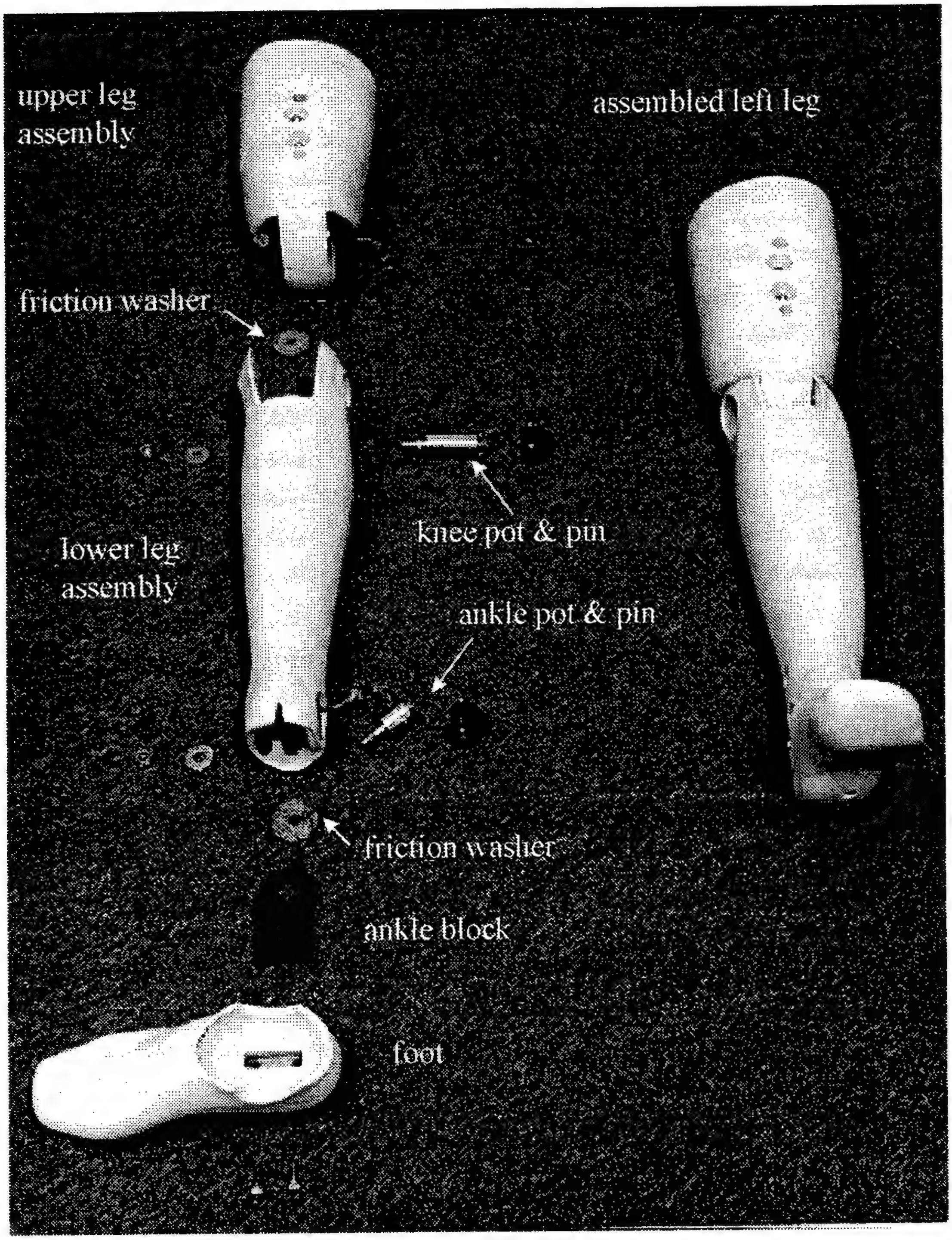


Figure 20. Leg and Foot Assemblies

SWIM Instrumentation. SWIM instrumentation consists of the following essential components.

MFG.		Description
EME Corp.	(1)	modified data acquisition system used in the Air Force's advanced dynamic anthropomorphic manikin (ADAM)
SOL TEC	(1)	triaxial accelerometer
KVH Industries	(1)	mechanically gimbaled flux gate compass
Micro Pneumatic Logic, Inc.	(4)	pressure sensors
Spectron Glass & Electronics, Inc.	(1)	tilt & roll sensor
Maurey Instrument Corp.	(21)	potentiometers
C.M. Hammar Handels AB	(1)	hydrostatic release
Remtron	(1)	radio remote control system

Remote Start/Stop Data Acquisition. SWIM data collection can be started remotely with a radio control system. At 100 samples per second on each of the 32 channels the data recorder will gather information for 43 minutes. The data are then retrieved from the mankin's memory and downloaded directly to a PC.

Mouth Splash Detection System. The open mouth is approximated by a 1/4-inch by 1 1/2-inch slot. The water is funneled into a removable plastic bag which can be weighed to determine the amount of water ingested.

Emergency Flotation System. A mechanical hydrostatic release will be used to activate a $C0_2$ cartridge which will inflate a bladder to recover SWIM if he sinks to a specified depth.

Expandable Thorax Volume. The chest segment has a constant mass but an expandable thorax volume. This approximates the volume change in the air retained in the lung between an unconscious and a conscious person taking a full breath and the associated chest expansion. The original approach to have an inflatable bladder beneath the chest skin was abandoned. The designs and prototype developed demonstrated that a robust system could not be developed. Instead, SWIM will have two fixed sizes of chest skins. This feature will allow SWIM to duplicate a variety of *floaters* and *sinkers*. A floater is a person who will float no matter how much air is expired due to the individual's low body density and a sinker will virtually sink even with a lung full of air due to his high body density. The range in volume is approximately 0 to 10 lb. of buoyancy.

The physical structure of the thorax design approximates the lower floating rib which duplicates the resistance of PFD to vertical body motion, i.e., prevents the PFD from riding up.

Variable Ballast. Variable ballast is designed into SWIM and is comprised of combinations of lead and delrin disks installed in the chest region. This will be used to account for any future hardware changes or required buoyancy adjustments.

Joint Resistance. The present joint resistance design of SWIM can only simulate an unconscious PFD user except for special test scenarios where the locking of joints can be used evaluate unique body positions, e.g., heat escape lessening posture (HELP). The joint resistance is accomplished with a frictional pad control system and is measurable and repeatable for a particular testing scenario. The range of torque resistance will be adjustable from no resistance to that value required to hold the articulated segment in any given position.

Joint Restoring Torque Design Provisions. Provisions have been made in the design for adding restoring torque coil spring mechanisms which when loaded will return the segments to an adjustable preset condition.

In order to keep development and construction costs under 250 thousand dollars, much of the technology that went into SWIM was leveraged off of proven multi-million dollar designs such as the U.S. Air Force's Advanced Dynamic Anthropomorphic Manikin (ADAM) and automotive HYBRID II and III crash test dummies. Most of the skin molds used were based on HYBRID II. However, some components used were HYBRID III standards such as SWIM's hands.

4.3 SWIM Data Acquisition System (DAS)

The DAS being used in SWIM is the same system used in the Air Force's Advanced Dynamic Anthropomorphic Manikin (ADAM). The DAS, produced by Electro Mechanical Engineering Corporation of Arnold MD, can collect and store data from 32 channels. It can collect data for 43 minutes at a sampling rate of 100 samples per second/channel. It has a 16-bit A/D converter, 12-pole anti-aliasing filters, shunt calibration, and is powered by NiCad rechargeable batteries. An external standard PC/AT microcomputer, communicating with the DAS through the RS-232 port of the microcomputer, is used to run a computer program with menu-selectable routines for sensor calibration, configuring the system, and downloading the test data. Through a radio link, the DAS can be started, stopped and restarted at the discretion of the operator. An overview of SWIM's instrumentation is shown in Figure 21. After downloading the data from SWIM, the user can display and analyze the results on the host computer. The raw data can be displayed graphically on the computer screen in engineering units. The data can also be filtered, decimated, and converted to an ASCII file for importation into other

software analysis and display programs, e.g., SWIMVU. Additional details can be found in the DAS-32S User's Manual in Reference (14).

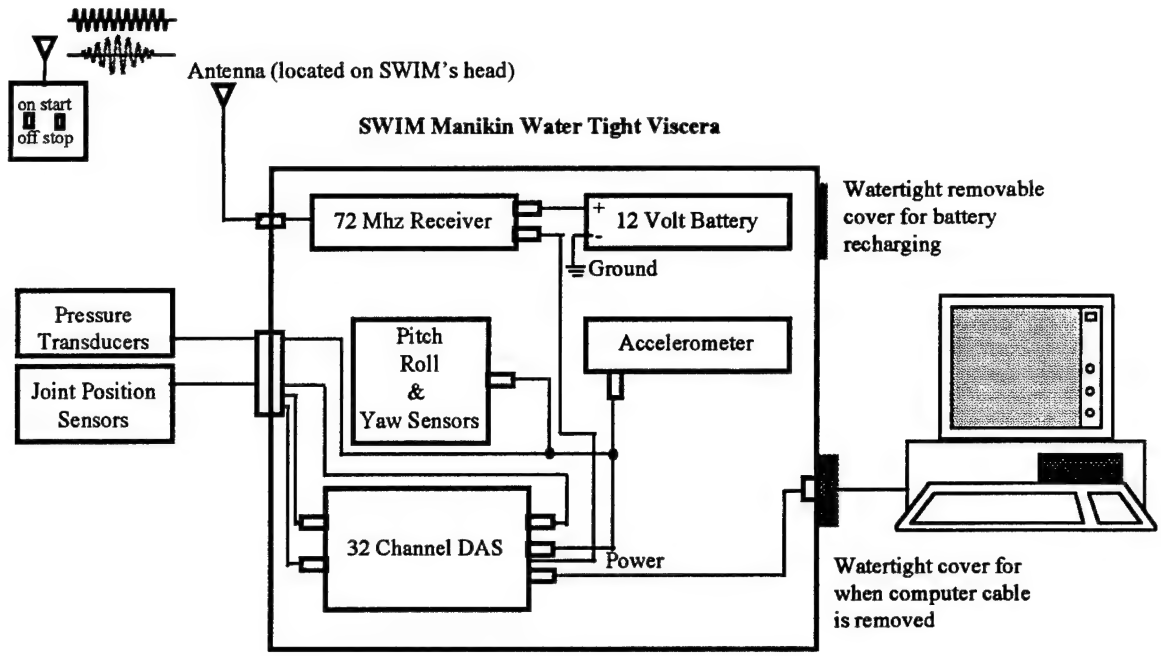


Figure 21. SWIM Instrumentation Overview

4.4 SWIM Hydrostatics

Although SWIM segments were designed with the mass, centers of mass, and mass moments of inertia representative of a mid-size male it was important to consider the volumetric profiles of SWIM segments as compared to human segments. SWIM is a mechanical representation of a human being. Therefore, some short comings in SWIM human fidelity are expected. The SWIM manikin can have utility to the ATB validation efforts and future PFD/manikin experiments only if it can approach the flotation characteristics of a person. SWIM would have little value as a tool if it had inappropriate buoyancy moments in his legs, arms, and torso which made him float uncharacteristically of that of a person.

Melville Shipping Ltd. compared the SWIM manikin volume distribution to available photogrammetric data on humans in Reference (15). Figure 22 presents a volumetric comparison of two human males and SWIM based on a cumulative volume plotted against percentage of height. The data are presented in percentage of height to provide a more direct comparison of cumulative volumes even though the subjects and SWIM are different heights. The basic height, weight, and volume differences between the male subjects and SWIM are:

Table 2 - Volumetric Comparison of SWIM manikin to Human Subjects

	Height	Wgt.(in Air)	Volume	Displ. (in fresh H_20)	Wgt.(in H_20)
SWIM	68"	169lb	2.1ft^3	133lb	36lb
TIL (human male)	67"	155lb	2.3ft^3	142lb	13lb
TLB (human male)	70"	169lb	2.5ft^3	159lb	10lb

note: TIL and TLB represent typical small and large male characteristics, respectively

Figure 22 demonstrates that SWIM's volume distribution is similar to the human subjects except for the apparent discontinuity in the hip region. This is where the joint void spaces have a significant impact on its volumetric distribution. The measurements in Reference (15) demonstrated that SWIM's total buoyancy in fresh water is more than 30 lb less than its weight.

Armstrong Laboratory at WPAFB has performed a new weight balance to correct the buoyancy deficiency in SWIM. Corrective action is in progress by the fabrication of lighter skins and a strategic weight reduction in the skeletal structure to provide a 15 lb (6.8 kg) positively buoyant manikin.

4.5 SWIMVU

SWIM has been intentionally outfitted with sufficient sensors to allow for the experimental display of the general body response to real wave induced motions. In order to display these motion responses the U.S. Air Force's DYNAMAN program was adapted to animate the experimental data collected with SWIM. HYBRID III manikin geometry, obtained from the Generator of Body Data (GEBOD) program (Reference (16)) were used to approximate SWIM geometry.

The baseline reference point for the measured joint articulations is the 6-DOF measurement system in SWIM's chest cavity. Additionally, SWIM records 21-joint articulations from head rotation to knee flexion. These are recorded with potentiometers and are referenced to the 6-DOF chest cavity for generating the whole body experimental motion response to waves. The animation model includes a simple plane to represent the wave slope cross-section through the body. The relative position of this wave plane to the body is inferred from the pressure transducers located on the upper chest near each armpit and two on the upper buttocks.

The SWIMVU animation program imports an ASCII time series file from SWIM's DAS which contains the channel numbers corresponding to the different sensors, such as the potentiometers and pressure transducers. Post processing tables and graphs include the option of displaying dynamic variables of freeboard and angle of repose. SWIMVU will permit the side-by-side display of experimental and analytical data. A qualitative sense of

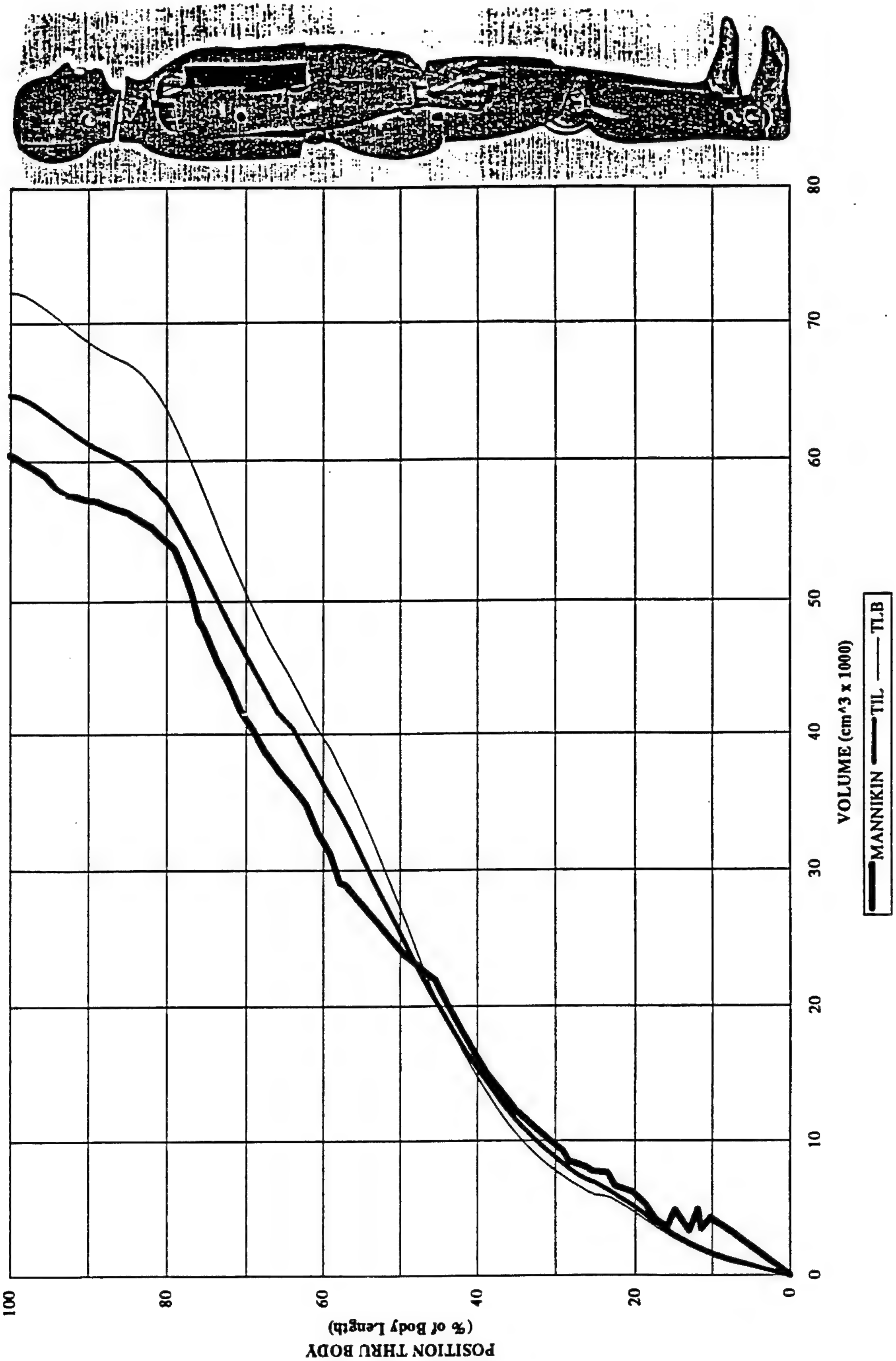


Figure 22. Comparison of Manikin and Human Subject Volume Distributions

correlation can be obtained from the 3D wire frame animation's, and quantitative comparisons can be made with time history overlays of experimental and ATB simulation results. SWIMVU will prove to be an invaluable tool for future planned full-scale validation efforts. It was used for validation efforts with simple shapes, e.g., ellipsoids, in Reference (8). At present, the SWIMVU software can only depict the mean water line for simulations whether they take place in calm water or in waves.

5.0 CONCLUSIONS AND FUTURE EFFORTS

5.1 New Research Tools Developed

The new instrumented flotation manikin and simulation software will contribute towards establishing optimum performance requirements for PFDs to enhance boater safety. The instrumented manikin will provide a new research tool to the Transport Canada and the U.S. Coast Guard. It will be used to collect quantitative data to determine human survivability in rough water. The manikin will provide a new standard for providing a no-risk to human subjects, reliable, and repeatable approach to improving our understanding of the interaction of persons in waves. SWIM experiments can be designed that will quantify factors that influence survivability in rough water.

The WAFAC adaptations to the ATB program, once validated, will provide a means of testing survival gear on various cross-sections of the population including children.

5.2 PFD Performance

Some specific parameters that may be relevant to assessing human survival in rough water can be derived from the WAFAC model. They include time histories of the following:

Buoyancy - Buoyancy time histories could indicate sensitivities of the person wearing a PFD to passing wave peaks and wave troughs.

Dynamic Freeboard - Dynamic Freeboard may well be the most significant performance measure. It is defined as the distance from the water surface to the lowest point on the mouth.

Waterplane Area - Waterplane area can be used to determine restoration factors. A damping factor can also be determined from a displacement time history at some anthropometric landmark such as the center of a persons chest.

Body Repose Angles - The body repose angles can provide information on turning times. There are two angles of concern. These are the face plane angle and trunk angle.

The ATB program has great flexibility in that the user can select any body landmark and require the program to provide acceleration, velocity, displacement, and any water forces times histories of interest. New performance measures will assist in developing improved standards, probability of survival data, and future guidance to the boating public in selecting the optimum flotation aid.

5.3 Future Research Focus

5.3.1 Validation with Simple Geometric Shapes

The flotation attitude of a human body in waves is governed in large part by the position of the head and limbs. Changes in these positions will be forced by flow past the limbs of the person. The hydrodynamic contribution of these individual parts will influence the flotation attitude and the amount of water ingested by a person. Although some initial work has been performed in generating experimental data and simulations on simple shapes approximating human segments, future attention is needed to validate a reasonable model. The work performed by IMD and GESAC, Inc. in these initial tests have evoked a number of questions such as:

- How sensitive is added mass to proximity effects of the water's surface?
- What is the influence of wave damping effects on the motions of a predominantly submerged floating person?
- Will human segment blocking effects in waves need to be modeled?(Segment blocking effects refer to the literal blocking of water flow by one segment directly in front of another. The discounting of these hydrodynamic blocking effects may cause over estimations of water forces on combined segments)

The ultimate goal of these experiments is to find the best model and optimum hydrodynamic coefficients for use with the ATB program. The result of this work will be the selection of a model and a table of hydrodynamic coefficients which may consist of a hybrid of experimentally derived and theoretical values.

5.3.2 Full-Scale Validation Testing

Full-scale validation testing will involve the SWIM manikin. Controlled tests in a wave tank will exercise the model and permit a level of fine tuning. The manikin tests will determine the range of usefulness of the selected model in terms of modeling persons in waves as opposed to ellipsoids. Tests will be conducted without PFDs attached and with a variety of PFDs attached. ATB simulation studies will be performed and compared to the experimental data using SWIMVU. At present full-scale testing is planned for the fall of 1997 at IMD.

5.3.3 End-User Program Interface

Although, the Coast Guard establishes the technical and testing requirements for Coast Guard approved survival equipment, industry is responsible for the development expense and testing of their own equipment. Industry will be consulted on a pre-processor interface for the program after sufficient confidence is built in the WAFAC prediction model. Presently, the computer program requires expertise to configure a simulation. Work will be done to improve the user interface to make it more accessible to the practical designer. A pre-processor will be developed to allow the input of PFD attachment data and wave conditions for sets of standardized initial conditions in a user friendly format and a post-processor will be developed to better handle the output time histories and graphics.

5.3.4 Research Risks and Benefits

This research is not without risk. There is both cost and technical risk. There is technical risk with regard to the ultimate usefulness and contribution to the understanding of the performance of PFDs in rough water. The modeling of a floating object in waves is difficult and the successful simulation of multiple linked objects, as in the case of a person wearing a lifejacket, is even more difficult. The final model may be limited to linear waves and although, this would not completely achieve the objective of truly simulating a person's response in rough water, it will still provide useful data beyond the present knowledge base of calm water effects. There is cost risk with regard to the expense associated with a long and exhaustive validation effort.

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